

Utilization of Dependency Structure Matrix Analysis to Assess Implementation of NASA's Complex Technical Projects

by
Timothy K. Brady

B. S. Mechanical Engineering, University of Notre Dame, May 1982

M. S. Mechanical Engineering, University of Kentucky, December 1984

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the
Massachusetts Institute of Technology

February 2002

© Timothy K. Brady, All Rights Reserved.

The author hereby grants to MIT permission to reproduce and distribute publicly paper and electronic copies of this thesis in whole or in part.

Signature of Author _____
Timothy K. Brady
System Design and Management Program
December 17, 2001

Certified by _____
Deborah J. Nightingale
Thesis Supervisor
Professor of Practice of Aeronautics and Astronautics and Engineering Systems

Accepted by _____
Steven D. Eppinger
Co-Director, LFM/SDM
GM LFM Professor of Management Science and Engineering Systems

Accepted by _____
Paul A. Lagace
Co-Director, LFM/SDM
Professor of Aeronautics & Astronautics and Engineering Systems

Utilization of Dependency Structure Matrix Analysis to Assess Implementation of NASA's Complex Technical Projects

by

Timothy K. Brady

Submitted to the System Design and Management Program
on December 17, 2001 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Engineering and Management

ABSTRACT

The National Aeronautics and Space Administration (NASA) has built a great history for achieving remarkable success in accomplishing complex technical tasks. During the 1970's and 1980's, planetary spacecraft were sent throughout our solar system which provided close-up views of the planets. However, the 1990's arrived with some project failures including a flaw in the Hubble Space Telescope's primary mirror, and the loss of three spacecraft sent to Mars.

Following the determination of the cause for the 1999 loss of Mars Climate Orbiter, the mishap investigation board reviewed eight previous failure investigation reports and identified a correlation between other project failures and a few common themes. The most common themes included inadequate project reviews, poor risk management, insufficient testing, and inadequate communications. Most project managers are aware of the possibilities of and the consequences of these risk areas in complex technical projects – so why do many projects make these same mistakes?

This thesis developed a framework for evaluating the long-term effect of early project implementation decisions. Early decisions, such as establishing a system architecture and selecting technology of particular maturity, can have lasting impact throughout the project development process and during the project's operation phase. A systems engineering analysis framework using two different extensions of dependency structure matrix (DSM) analysis was developed to provide a comprehensive system view of the project architecture and the technology choices. An "interface DSM" mapped the dependence of components on one another and identified the impact of component criticality on the mission operations. A "technology risk DSM" included a component technology risk factor to help identify the patterns of system level risk. The ultimate goal of this thesis was to develop an analytical framework that could be used, along with other sound system engineering tools, to expand the management team's holistic view of the project, which could then be used to enhance project implementation decision-making.

The analytical framework developed in this thesis was applied to seven spacecraft projects which served as case studies. Successful and unsuccessful projects were included in the set of cases. Analytical observations were compared to post-project lessons learned to develop a general understanding of the relationship between the project structure and the implementation approach for each case.

Thesis Supervisor: Deborah J. Nightingale

Title: Professor of Practice of Aeronautics and Astronautics and Engineering Systems

Biographical Information

Mr. Brady has worked at NASA's Johnson Space Center since 1985 and has held assignments related to managing testing of advanced thermal control system technologies and the developing equipment for astronaut's use during extravehicular activities (EVAs) or spacewalks. From 1994 through 1997, Mr. Brady served as project manager for the development of two Shuttle flight experiments to demonstrate EVA tools and techniques for assembling and maintaining the International Space Station (ISS). Mr. Brady is currently assigned to the EVA Project Office and is overseeing development of new EVA items for ISS.

Mr. Brady received a Bachelor of Science degree in Mechanical Engineering from the University of Notre Dame in May 1982 and a Master of Science degree in Mechanical Engineering from the University of Kentucky in December 1984.

Acknowledgements

Participation in the System Design and Management Program has been a tremendous experience for me and I would like to gratefully acknowledge the sponsorship provided by NASA Headquarters and NASA's Johnson Space Center (JSC). In particular, I would like to thank the EVA Project Office at JSC for their efforts to make this experience as easy as possible, especially Greg Harbaugh, Steve Poulos, Allen Flynt, Glenn Lutz, and Mary Chesler.

I would like to thank my classmates who have made this experience over the past two years an exciting journey. The conversations, the collaboration and the new friendships have been the highlight of this program.

I would like to express appreciation to my thesis adviser, Professor Debbie Nightingale. I have appreciated your encouragement and I have enjoyed the exchange of ideas that helped to formulate this work.

I would like to dedicate this work to my parents, Bob and Cora Brady, who have given so much of themselves to provide opportunities for Pat, Mike, Georgeann, Gretchen, Terry and myself. This work would not have been possible without their love and support.

Finally, I would like to express my love and gratitude to my wife – Rita, thanks for joining me on life's wonderful adventure.

Table of Contents

ABSTRACT.....	3
Biographical Information.....	5
Acknowledgements	7
List of Figures	11
List of Tables	11
Acronyms	13
Chapter 1 Introduction	15
1.1 Motivation	15
1.2 Thesis Structure.....	18
Chapter 2 Utilization of the Dependency Structure Matrix to Enhance Project Planning Decisions..	19
2.1 Description of the Dependency Structure Matrix.....	19
2.2 Assessing Project Implementation with DSM Analysis	22
2.2.1 Interface DSM.....	23
2.2.2 Technology Risk DSM	25
2.2.3 Interface and Technology Risk DSM Analysis Process	28
Chapter 3 Project Case Study Analysis	31
3.1 Small Spacecraft Projects	32
3.1.1 Case 1: Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX)	32
3.1.2 Case 2: Clementine.....	38
3.2 Discovery Program.....	43
3.2.1 Case 3: Mars Pathfinder	44
3.2.2 Case 4: Near Earth Asteroid Rendezvous	54
3.3 Mars Surveyor Program.....	61
3.3.1 Case 5: Mars Global Surveyor	61
3.3.2 Cases 6 and 7: Mars Surveyor 1998 – Mars Climate Orbiter and Mars Polar Lander	66
Chapter 4 Discussion of Results.....	81
4.1 Summary of the Interface and Technology Risk DSM Case Study Analysis	81
4.1.1 System Architecture, Project Organization and Development Strategy	82
4.1.2 Risk Management.....	86
4.2 Observations from the DSM Case Study Analyses	88
4.3 Future Extensions of Interface and Technology Risk DSM Analysis	89
Chapter 5 Summary and Conclusions.....	91
Bibliography.....	93
Appendix – Case Study Analysis Assumptions	97

List of Figures

Figure 2.1-1 Simplified Example of a Task DSM.....	19
Figure 2.2.1-1 Example: Bicycle Interface DSM.....	23
Figure 2.2.2-1 Technology Risk DSM for the Bicycle Example	27
Figure 2.2.3-1 Overview of the DSM Analysis Process for the Bicycle Example.....	29
Figure 3.1.1.1-1 SAMPEX Spacecraft On-Orbit Configuration	33
Figure 3.1.1.1-2 SAMPEX Spacecraft Architecture.....	34
Figure 3.1.1.2-1 SAMPEX Interface DSM.....	35
Figure 3.1.1.2-2 SAMPEX Technology Risk DSM	35
Figure 3.1.1.3-3 SAMPEX Project and SMEX Program Responsibilities	37
Figure 3.1.2.1-1 Clementine Spacecraft	39
Figure 3.1.2.2-1 Clementine Interface DSM.....	41
Figure 3.1.2.2-2 Clementine Technology Risk DSM	42
Figure 3.2.1.1-1 Mars Pathfinder Entry, Descent and Landing Sequence	45
Figure 3.2.1.1-2 Mars Pathfinder Lander Configuration	46
Figure 3.2.1.2-1 Component DSM for Mars Pathfinder – JPL Subsystem Grouping	47
Figure 3.2.1.2-2 Mars Pathfinder Interface DSM.....	48
Figure 3.2.1.2-3 Technology Risk DSM for Mars Pathfinder.....	50
Figure 3.2.2.1-1 NEAR Mission Overview	54
Figure 3.2.2.1-2 NEAR Spacecraft Flight Configuration	56
Figure 3.2.2.2-1 NEAR Interface DSM.....	57
Figure 3.2.2.2-2 NEAR Technology Risk DSM	58
Figure 3.3.1.1-1 MGS Spacecraft – Orbiter Configuration.....	62
Figure 3.3.1.2-1 MGS Interface DSM	63
Figure 3.3.1.2-2 MGS Technology Risk DSM	64
Figure 3.3.2.1.1-1 MCO Spacecraft Orbiter Configuration	66
Figure 3.3.2.1.2-1 Mars Polar Lander: Flight and Landed Configurations.....	68
Figure 3.3.2.1.2-2 MPL Landing Sequence	69
Figure 3.3.2.2.1-1 MCO Interface DSM.....	70
Figure 3.3.2.2.1-2 MPL Interface DSM.....	71
Figure 3.3.2.2.2-1 MCO Technology Risk DSM	73
Figure 3.3.2.2.2-2 MPL Technology Risk DSM	74
Figure 4.1.1-1 Mapping of System Architecture for Cases Studied	83
Figure 4.1.2-1 NASA Risk Management Overview.....	86
Figure 4.1.2-2 Detailed View of the Mars Pathfinder Technology Risk DSM.....	87
Figure 4.3-1 EDL Subsystem Technology Risk Matrix at Concept Selection and at Launch	89

List of Tables

Table 2.1-1 Four Applications of DSM Analysis.....	20
Table 2.2.1-1 Matrix Values for Strength of Component Interface Dependence	24
Table 2.2.1-2 Matrix Values for Strength of Operation’s Dependence on a Component	25
Table 2.2.2-1 Technology Risk Factor (TRF).....	26
Table 3-1 Summary of Project Case Studies.....	31
Table 3.2-1 – Discovery Program Missions.....	44
Table 4.2-1 – Mars Surveyor Projects included in Case Studies.....	61

Acronyms

ACE	attitude control electronics
AIM	Attitude and Information Management
ALTO	assembly, test and launch operations
APL	Applied Physics Laboratory
APXS	Alpha Proton X-ray Spectrometer
ASI	Atmospheric Structure Instrument
BMDO	Ballistic Missile Defense Organization
C&DH	command and data handling
CT&DH	command, telemetry, and data handling
CTT	command telemetry terminal
DoD	Department of Defense
DPU	data processing unit
DS-2	Deep Space 2
DSM	dependency structure matrix
DSN	Deep Space Network
EDL	entry, descent and landing
EVA	extravehicular activity
G&C	guidance and control (G&C)
GSFC	Goddard Space Flight Center
HGA	high gain antenna
HILT	Heavy Ion Large Telescope
ICD	Interface Control Document
IMP	imager for Mars Pathfinder
IMU	inertial measurement unit
INCOSE	International Council on Systems Engineering
ISS	International Space Station
JSC	Johnson Space Center
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
LEICA	Low Energy Ion Composition Analyzer
LIDAR	Light Detection And Ranging
LMA	Lockheed Martin Astronautics
MARCI	Mars Color Imager
MARDI	Mars Descent Imager
MAST	Mass Spectrometer Telescope
MCO	Mars Climate Orbiter
MET	meteorology package
MGS	Mars Global Surveyor
MIB	Mishap Investigation Board
MOI	Mars orbit insertion
MPL	Mars Polar Lander
MSOP	Mars Surveyor Operations Project
MVACS	Mars Volatiles and Climate Surveyor
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NRL	Naval Research Laboratory
OSTP	Office of Science and Technology Policy

Acronyms (Continued)

PET	Proton/Electron Telescope
PMIRR	Pressure Modulator Infrared Radiometer
PMIRR	Pressure Modulator Infrared Radiometer
PPS	Power and Pyrotechnic Switching
RPP	recorder/processor/packetizer
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SEDS	Small Explorer Data System
SMEX	Small Explorer
SRB	Special Review Board
TCM	trajectory correction maneuver
TRF	technology risk factor
TRL	technology readiness level
TTI	trans-lunar transfer injection
UHF	ultra high frequency
V&V	Verification and Validation

Chapter 1 Introduction

1.1 Motivation

The National Aeronautics and Space Administration (NASA) has built a great history for achieving remarkable success in accomplishing complex technical tasks. In the 1970's, the Viking Program sent orbiters and landers to Mars, greatly expanding our knowledge about Earth's sister planet. The Voyager I and II spacecraft, on a more than decade-long voyage through our solar system, provided close-up views of the outer planets. In the 1980's, large planetary spacecraft, such as the Magellan to Venus and Galileo to Jupiter, were launched on long journeys to their respective destinations. However, the early 1990's arrived with some project failures. In April 1990, the Hubble Space Telescope was launched with a flaw in its primary mirror, and in 1993, the Mars Observer was lost shortly before it was to enter Mars orbit.

In the mid to late 1990's NASA looked to smaller projects with shorter development times and many spacecraft in this era demonstrated new technology and returned valuable science. For example, the Pathfinder landed on Mars in 1997 delivering close-up views of the surface and demonstrating the use of a small robotic rover. The Near Earth Asteroid Rendezvous spacecraft, launched in 1996, became the first probe to provide detailed information about an asteroid. These successes however were offset with some failures, most notably the loss of both the Mars Climate Orbiter and the Mars Polar Lander in 1999. During the review of the Mars Climate Orbiter loss, the mishap investigation board reviewed eight previous failure investigation reports and identified "a high correlation of failures connected with a few themes."¹ The most common themes identified included inadequate project reviews, poor risk

¹ Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," March 2000, p. 33.

management, insufficient testing, and inadequate communications. Most project managers are aware of the possibilities of and the consequences of these risk areas in complex technical projects – so why do many projects make these same mistakes?

Blanchard and Fabrycky (1998) noted the importance of having a life cycle view of a project from the very start. “It is essential that engineers be sensitive to utilization outcomes during the early stages of system design and development, and that they assume the responsibility for life cycle engineering that has been largely neglected in the past.”² This thesis focuses on the impact early project planning decisions have on the entire project life cycle. In complex technical projects the responsibility for understanding the broad view of a project falls upon the shoulders of the systems engineer. NASA’s Systems Engineering Handbook views systems engineering as a “robust approach to the design, creation, and operation of systems.”³ The systems engineering process is a continual process of gathering information from the system’s perspective, developing design alternatives, evaluating these alternatives, and making decisions in the best interest of the whole. This role is not an easy one. The International Council on Systems Engineering (INCOSE) noted that as complexity has increased in a development activity, the engineering disciplines and organizations have become fragmented in order to deal with complexity. The fragmentation of a complex problem leads to a tendency for disciplines to optimize their subsystem at a local level; however this approach may not be optimal for the system. “This inability to recognize that system requirements can differ from disciplinary requirements is a constant problem in systems development. The systems engineering process can be viewed as a major effort in communication and management of complex teams of experts that lack a common paradigm and a common language.”⁴

² Blanchard, Benjamin S. and Fabrycky, Walter J., *Systems Engineering and Analysis – Third Edition*, (Upper Saddle River, NJ: Prentice Hall, 1998), p. 19.

³ National Aeronautics and Space Administration, “NASA Systems Engineering Handbook,” SP-6105, June 1995, p. 4.

⁴ International Council on Systems Engineering, *Systems Engineering Handbook*, Release 1.0, January 1998, p. 4.0-1.

Systems engineering techniques are tools that support information discovery and can be used to communicate those discoveries to a variety of technical disciplines. The real value of a tool is to facilitate a meaningful discussion on options and possibilities. When multiple stakeholders are required to resolve issues or offer an optimal system design, it is necessary to have a tool that enhances the group discovery process. NASA's view of the systems engineering process is "identification and quantification of systems goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post implementation assessment of how well the system meets (or met) the goals."

This thesis developed a framework for evaluating the long-term effect of early project implementation decisions. Early decisions, such as establishing a system architecture and selecting technology of particular maturity, can have lasting impact throughout the project development process and during the project's operation phase. This analytical framework was developed to provide a comprehensive system view of the project architecture and the technology choices. The ultimate goal of this thesis was to develop an analytical framework that could be used, along with other sound system engineering tools, to expand the management team's holistic view of the project, which could then be used to enhance project implementation decision-making.

Seven spacecraft projects served as case studies using the analytical framework developed in this thesis. Successful and unsuccessful projects were included in the set of cases. Analytical observations were compared to post-project lessons learned to develop a general understanding of the relationship between the project structure and the implementation approach for each case. For example, was the organizational approach aligned with the system architecture to optimize information flow? If not, were strategies put in place to address the needs of communication? How did the inherent technology risk of a component impact the overall system risk? Were mitigation strategies put in place to address the component and system performance risk?

1.2 Thesis Structure

The proposed systems engineering analysis framework was demonstrated through the use of case studies of complex spacecraft projects. By demonstrating the analysis tool on well-documented projects, the thesis intends to encourage use of sound systems engineering tools in analyzing project architectures and technology choices during the early phases of project planning. The thesis is presented as follows:

Chapter 1 describes the motivation for the work of this thesis and describes the goal to develop a systems engineering analytical framework that could be used to enhance decision-making related to project implementation.

Chapter 2 describes the history of dependency structure matrix analysis and describes an extension of previous work as a systems engineering analysis framework to examine complex technical projects.

Chapter 3 applies the systems analysis framework to seven case studies of projects that developed and operated complex spacecraft for either Earth observation or interplanetary exploration. By reviewing lessons learned from specific projects, an assessment is made as to whether early project management decisions created a fundamental project implementation structure that contributed to the successful or unsuccessful completion of the project.

Chapter 4 summarizes the results of utilizing the system analysis framework as a tool to identify fundamental project structure and implementation strategies associated with successful or failed cases. A critique of the analysis framework is presented and recommendations for future work are presented.

Chapter 5 provides a brief summary of the analysis that was performed, draws conclusions related to the capabilities of the analytical framework, and identifies insights gained related to successful projects.

Chapter 2 Utilization of the Dependency Structure Matrix to Enhance Project Planning Decisions

2.1 Description of the Dependency Structure Matrix

The use of the design structure matrix, or dependency structure matrix (DSM), was described by Steward in the 1980's (Browning 1998a, Ulrich 2000) for the analysis of the structure of a system's design.⁵ Browning noted the advantages of dependency matrix-based analysis: "Their utility in these applications stems from their ability to represent complex relationships between the components of a system in a compact, visual, and analytically advantageous format."⁶

Eppinger, Whitney, Smith and Gebala (1994) provide an overview of the basic DSM described by

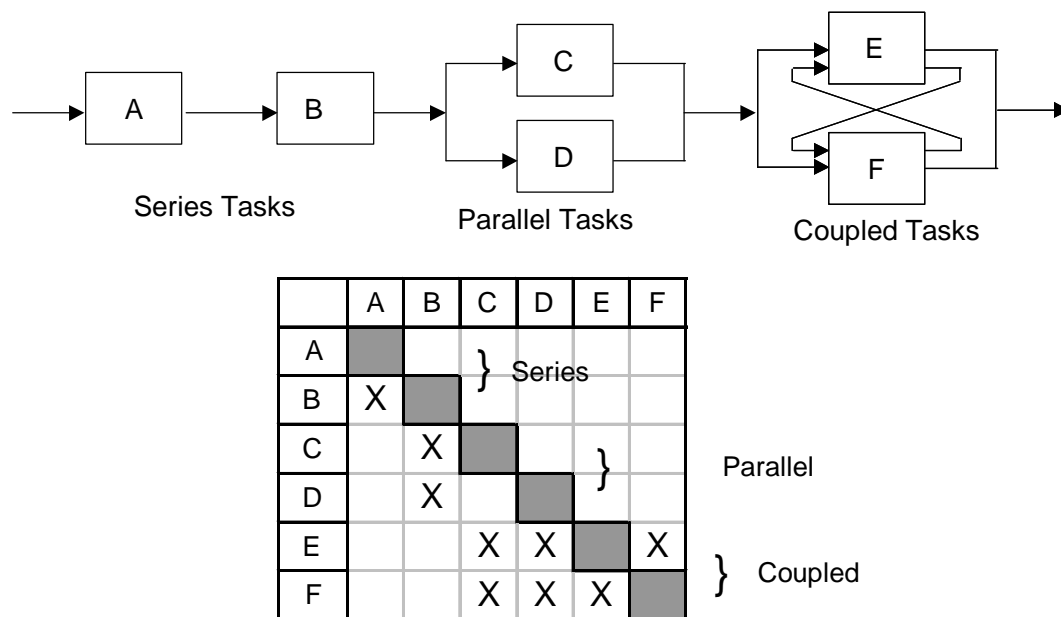


Figure 2.1-1 Simplified Example of a Task DSM

⁵ Steward's work has been cited in Browning, Tyson R., "Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development," PhD Dissertation, Massachusetts Institute of Technology, December 1998. (1998a) and Ulrich, Karl T. and Eppinger, Steven D., *Product Design and Development*, McGraw Hill, 2000.

⁶ Browning (1998a), p. 98.

Steward to represent the dependence of tasks on one another. In the sequence of tasks in Figure 2.1-1, A and B are in series; C and D are in parallel; and E and F are coupled. In the DSM, tasks in the rows and columns are identically labeled. The marked elements in a row indicate which other tasks contribute information to the row's task. Since A and B are in series, task B requires information from task A. Parallel tasks C and D require information only from task B. The coupled tasks E and F require information from tasks C and D as well as each other. The blocks with marks below the diagonal indicate information is fed forward to later tasks. The one mark above the diagonal indicates that information from task F must be fed backward to task E prior to its completion. This type of configuration in a task DSM provides an indication of a feedback loop or design iteration. Once the information flows are documented in a DSM, an analytical reordering is performed to sequence tasks such that the number of feed-forward tasks (tasks below the diagonal) is maximized while the number of tasks requiring feedback is minimized.

Since Steward's work in the 1980's the use of DSM has been extended to other types of system and design analysis. Browning (1998a) describes four applications of the DSM for addressing different types of problems. Table 2.1-1 provides a brief overview of these four types.⁷

Table 2.1-1 Four Applications of DSM Analysis

DSM Type	Description
Component-Based or Architecture DSM	Used for modeling system architecture based on component interrelationships
Team-Based or Organization DSM	Used for modeling organization structure based on information flow between people and other groups
Activity-Based, Task-Based or Schedule DSM	Used for modeling project schedule and activity sequencing based on interactivity information flow
Parameter-Based or Low Level Schedule DSM	Used for modeling low level relationships between design decisions and parameters, systems of equations, subroutine parameter exchange, etc.

DSM has been used extensively to model complex product development processes and to suggest

⁷ Browning (1998a), p. 99.

optimized structure and strategy for improved performance. Eppinger et al. (1994) described an extension of the binary structure in Steward's task DSM by including a measure of the degree of dependence between tasks and accounting for the tasks' durations. This extension provided a means for giving preference in the matrix manipulation to stronger dependencies over weaker ones. They used this method to recommend reorganizing a complex design process to improve product development time. Browning (1998b) identified many of the challenges to reducing product development cycle time and pointed out advantages for using an activity DSM to address those challenges.

McCord and Eppinger (1994) demonstrated the use of a team-based DSM to describe the patterns of required information exchange for an automobile engine development team. They suggested reorganization of the systems teams to optimize exchange of information. Pimmler and Eppinger (1994) extended this work by presenting a methodology for the analysis of product design decompositions. They also identified four important types of interactions between elements in a component DSM and provided a method for quantifying the strength of these interactions.⁸ The four component interaction types were:

- spatial interaction – identifies need for adjacency or orientation between elements;
- energy interaction – identifies needs for energy transfer;
- information interaction – identifies need for information or signal exchange between the two elements;
- material interaction – identifies need for materials exchange between elements.

Eppinger (1997) showed the use of both the team-based DSM and the above component interaction quantification in a component DSM to demonstrate a method for integration analysis of large-

⁸ Pimmler, Thomas U. and Eppinger, Steven D., "Integration Analysis of Product Decompositions," DE-Vol. 68, *Design Theory and Methodology – DTM '94*, ASME 1994.

scale engineering systems. Eppinger and Salminen (2001) extended earlier works by using DSM to understand patterns in the complexity of product development from three views: a process view, a product view and an organizational view.

2.2 Assessing Project Implementation with DSM Analysis

This thesis explored the fundamental structure of project implementation strategy by examining the contribution early implementation approaches make toward the overall success or failure of a project. As Senge notes, the basic structure of a system influences the behavior of those involved. “We must look into the underlying structures which shape individual actions and create the conditions where types of events become likely.”⁹ DSM analysis was used to examine the fundamental project implementation structure of several NASA planetary and earth observation spacecraft projects. This thesis specifically examined cases of robotic spacecraft projects with costs less than \$300 million and development time to launch of approximately three years. The cases analyzed represented both successful and unsuccessful NASA projects.

A component-based DSM was expanded to assess the impact of the choice of system architecture and the selection of components with varying levels of technology readiness on overall project success. The extension of the component-based DSM was novel in two primary respects. First, since NASA projects generally involve multi-phase operations of significant duration, the component DSM included an approach to examine the impact of component criticality on each of the major operational phases of the project. This extension of the DSM including the operations section and operational section was called an “interface DSM.” Second, a “technology risk” DSM was presented, using a measure of the inherent

⁹ Senge, Peter, “The Fifth Discipline: the Art and Practice of the Learning Organization, (New York: Doubleday, 1990), pp.42-43.

technology risk of a component, to demonstrate a method for assessing the impact of component technology maturity on the overall system.

2.2.1 Interface DSM

The interface DSM has two sections, a component interface dependence section and a section identifying the dependence of components on the operational phases. In the component section, the dependence of components on one another was measured based on a rating of the strength of the interface between the two components. In the operations section of the DSM, major operational phases were included in the DSM to provide an opportunity to view the impact of component criticality on the respective operational phases.

A simplified example of the elements of a bicycle and its operational phases was modeled in an interface DSM shown in Figure 2.2.1-1. The major hardware components and each major operational phase was listed in the column heading and repeated along the row heading. Each element matched with itself was marked with a darkened square, forming a diagonal in the matrix. An element matched with

		Components	Wheels	Gears	Chain	Pedals	Handlebars	Frame	Brake	Brake Handle	Gear Shift	Odometer	Operational Phases	Peddling	Coasting	Braking
Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N	
Wheels	A		4				2	4			2		4	4	4	
Gears	B	4		4						4			2			
Chain	C		4		4								4			
Pedals	D			4			2						4			
Handlebars	E						2		2	2	2		2	2	4	
Frame	F	2			2	2		2	2	2						
Brake	G	4					2		4						4	
Brake Handle	H					2	2	4							4	
Gear Shift	I		4			2	2						2			
Odometer	J	2				2										
Operational Phases	K															
Peddling	L	4	2	4	4	2				2						
Coasting	M	4				2										
Braking	N	4				4		4	4							

Figure 2.2.1-1 Example: Bicycle Interface DSM

elements other than itself intersected at a square off of the diagonal. At this off-diagonal square, a value representing the relative strength of the relationship between the elements was established. In this application of the DSM, the relative dependence of the elements on each other is assumed to be equal and thus a matrix symmetric about the diagonal is created.¹⁰

In the component section of the interface DSM, the matrix values were assigned based on the strength of the interface relationship between components. Borrowing from Pimmler and Eppinger (1994), the strength of interface dependence was defined based on spatial, energy and information dependence. In the component section of the DSM, points were allocated as indicated in Table 2.2.1-1 for each of the existing component interfaces.

Table 2.2.1-1 Matrix Values for Strength of Component Interface Dependence

Type of Element Interaction	Points
Physical Interface – a physical interface exists in the defined system architecture	2
Energy Interface – significant energy transfer exists between components in the defined system architecture	2
Information Interface – Case 1 – direct transfer of information between the elements Case 2 – information exchanged between the elements indirectly	2 1

The purpose of the rating the strength of component interfaces was to identify those with high interdependence. The value of each interface in the matrix was obtained by summing the points from the physical, energy, and information interaction. Some examples from the bicycle case in Figure 2.2.1-1 are provided below.

- The chain had a physical and energy interface with the pedal. Matrix rating: $2 + 2 + 0 = 4$.

¹⁰ As described in earlier applications of DSMs, particularly the task-based type DSM, the dependence is not necessarily equal thus matrices that are asymmetric are generally expected.

- The odometer had an informational interface with the wheels. Matrix rating: $0 + 0 + 2 = 2$.

In the operations section of the DSM, the matrix values were established at the intersection between a component and operational phase. The values in this portion of the DSM were assigned based on the tolerance to component failure during the particular operation. Table 2.2.1-2 shows the ratings of components with respect to operational phases:

Table 2.2.1-2 Matrix Values for Strength of Operation's Dependence on a Component

Type of Element Interaction during Critical Operations Phase	Points
Essential component – a single point or major component failure can cause failure in the specific operational phase	4
Critical component – a single point or major component failure can cause degraded operations during the specific operational phase	2

The purpose of rating the strength of dependency of a component on a particular operation is to describe the criticality of the component to operational performance. Again using the bicycle example in Figure 2.2.1-1:

- In the “Pedaling Phase,” the wheels, chain, and pedals are essential to the pedaling operation, thus wheel, chain, and pedal components have a value of “4” in that operational phase.
- In the “Coasting Phase,” the wheels are considered “essential” and the handlebars are considered “critical,” thus the component criticality ratings of “4” and “2” were given respectively.

Development of the interface DSM represented the first step in the analysis of the NASA case studies.

2.2.2 Technology Risk DSM

A second matrix was created which attempted to provide a view of the impact of technology choice on the overall project. The technology risk DSM assigned a numerical rating to components based

on an assessment of the risk of the component operating as designed. The technology risk rating utilized in this study was based on the criteria NASA uses for determining technology readiness level (TRL).¹¹ The TRL ranges from one to nine with a TRL value of one indicating that only basic engineering principles used in the design have been observed and reported, while a TRL value of nine refers to a system that has been “flight proven” through successful mission operations. (See column 3 of Table 2.2.2-1)

For valuing matrix entries in the technology risk DSM, the NASA TRL definitions were adopted, but the ratings were created based on a technology risk factor (TRF). The TRF scale assessed a value of one for the lowest-risk components and a value of five for the highest-risk or unproven technology components. Subsystem data from each project was reviewed and each component was assigned a TRF based on the criteria established in Table 2.2.2-1 below.

Table 2.2.2-1 Technology Risk Factor (TRF)

TRF	NASA TRL Definition	NASA TRL Level
1	Actual system “flight proven” through successful mission operations	9
2	Actual system completed and “flight qualified” through test and demonstration (ground or space)	8
2	System prototype in a space environment	7
3	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	6
4	Component and/or breadboard validation in relevant environment	5
4	Component and/or breadboard validation in laboratory environment	4
5	Analytical and experimental critical function and /or characteristic proof-of-concept	3
5	Technology concept and/or application formulated	2
5	Basic principles observed and reported	1

¹¹ Several sources trace the origin of TRL definition to NASA’s Office of Aeronautics and Space Technology 1991 Integrated Technology Plan. The TRL definitions can also be found in: Sarsfield, Liam, “Cosmos on a Shoestring – Small Spacecraft for Space and Earth Science,” Rand Study for the Office of Science and technology Policy (OSTP) and the Office of Management and Budget, 1998.

2.2.3 Interface and Technology Risk DSM Analysis Process

The interface and technology risk DSMs described above were employed to analyze several complex NASA spacecraft projects. The DSM analysis methodology is described below:

1. The interface DSM was developed to identify dependence of components on one another based on criteria established in Table 2.2.1-1. The entry into a square of the component DSM was based on the values identified in Table 2.2.1-1. The dependence between two components was assumed to be associative, and the resulting matrix ended up being symmetric about the diagonal.
2. The elements in the interface DSM were clustered. Following the creation of the initial DSM, the components were reordered in the matrix. The criteria used for regrouping was one which placed the squares representing high interface dependency as close to the diagonal as possible. Using this strategy, components that have a high degree of interdependence will tend to form clusters. Since these DSMs were of moderate size, it was found that it was acceptable to perform this activity by inspection using a spreadsheet.¹²
3. The component dependence on operations was added to the interface DSM. The major operational phases were added to the bottom of the interface DSM. The operational phase's dependency on the component was included in the matrix according to Table 2.2.1-2. This step completed the formation of the interface DSM.
4. The TRFs for each of the elements (both components and operations) were assigned based on Table 2.2.2-1. The technology risk values were calculated and a technology risk DSM was completed.

Figure 2.2.2-1 shows the completed process for the bicycle example. The first step shows the completion of component interface dependency identification. The second matrix shows that in step 2,

¹² Several algorithms have been developed for manipulation of DSMs. A description of these tools can be found at http://web.mit.edu/dsm/DSM_tools.htm.

the components have been reordered and a set of three distinct clusters can be seen: the brake subsystem, the power subsystem and the monitor and control subsystem. In step 3, at the bottom of the second matrix, the operational dependence on components has been added. Finally, in step 4, the component TRFs have been added and the set of technology risk values for the entire matrix have been calculated.

The analysis process described above was followed for each of the NASA case studies. Once these two matrices were generated, the patterns of clusters and values in the interfaces or technology risk DSMs were studied. These patterns were then associated with lessons learned or observations made about the completed NASA spacecraft projects.

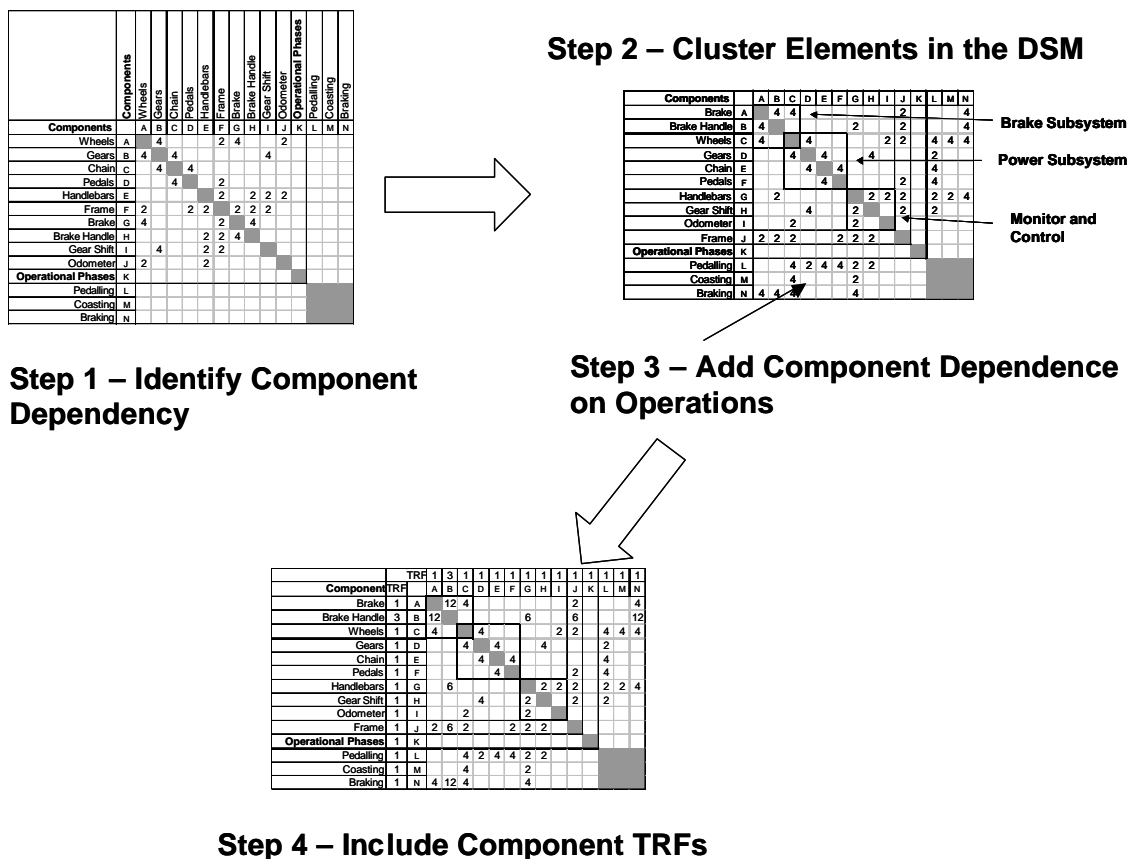


Figure 2.2.3-1 Overview of the DSM Analysis Process for the Bicycle Example

Chapter 3 Project Case Study Analysis

Seven case studies of planetary and earth observation spacecraft were selected for interface and technology risk DSM analysis:

- The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), the first spacecraft in the NASA Small Explorer Program;
- Clementine, a joint Department of Defense and NASA Program.
- Near Earth Asteroid Rendezvous (NEAR) and Mars Pathfinder in NASA's Discovery Program; and
- Mars Global Surveyor (MGS), Mars Climate Orbiter (MCO), and Mars Polar Lander (MPL) in the Mars Surveyor Program.

The cases selected all represent complex technical projects with budgets ranging from \$30 to \$300 million, and development time to launch of approximately three years. The cases presented an opportunity to examine a variety of implementation approaches such as the choice of system architecture and the utilization of advanced technology. Table 3-1 provides a summary of the project case studies.

Table 3-1 Summary of Project Case Studies

Project Category	Case Number	Project	Notes
Small Spacecraft	1	SAMPEX	Successful Earth observation spacecraft
	2	Clementine	Successful lunar exploration spacecraft
NASA's Discovery Program	3	Mars Pathfinder	Successful Mars lander
	4	NEAR	Successful asteroid rendezvous
Mars Surveyor Program	5	MGS	Successful Mars orbiting spacecraft
	6	MCO	Unsuccessful Mars orbiter
	7	MPL	Unsuccessful Mars lander

3.1 Small Spacecraft Projects

3.1.1 Case 1: Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX)

3.1.1.1 SAMPEX Mission and Spacecraft Description

The SAMPEX program was described by Baker et al. (1993) and Figueroa and Colón (1996). SAMPEX was the first of a series of missions in NASA's Small Explorer (SMEX) Program and was launched on July 3, 1992. NASA started the SMEX program in 1988 to develop more frequent, lower-cost science missions that could be launched on smaller expendable launch vehicles such as the Pegasus and Scout.

SAMPEX was designed to study the energy level and composition of particles originating from nearby and distant portions of the galaxy as well as monitoring magnetospheric particles. SAMPEX was designed to use the Earth's magnetic field as a giant magnetic spectrometer to separate different energies and charge states of particles as it circled the Earth in a near-polar orbit. Four science instruments were flown on SAMPEX and the spacecraft was designed to support a minimum mission of one-year with a goal to support three or more years. SAMPEX successfully completed its three-year mission goals in 1995.

A drawing of SAMPEX in its on-orbit configuration can be seen in Figure 3.1.1.1-1 and the spacecraft architecture can be found in Figure 3.1.1.1-2.¹³ SAMPEX was designed as a single-string system, and utilized a combination of flight-qualified hardware and new technology in a compact spacecraft design.

¹³ Both Figures come from Figueroa, Orlando and Colón, Gilberto, "SAMPEX," in *Reducing Space Mission Cost*, edited by Wertz, James R. and Larson, Wiley J., Space Technology Library, Microcosm Press, Torrance, CA, 1996, pp. 397-409, p. 400 and p. 402 respectively.

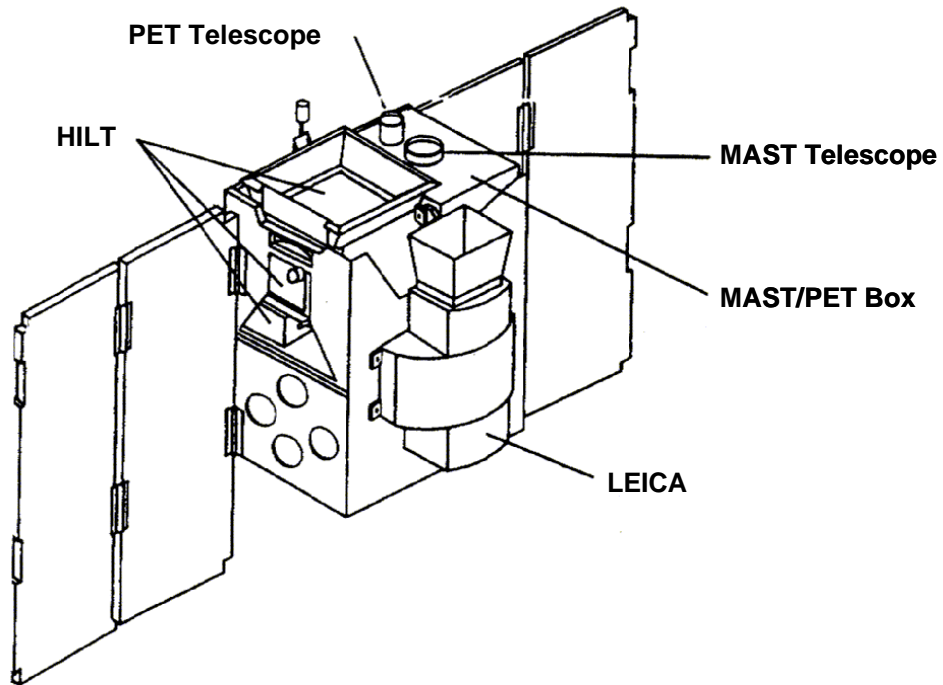


Figure 3.1.1.1-1 SAMPEX Spacecraft On-Orbit Configuration

Power supplied from the solar arrays, or from the battery during eclipse, was supplied to the spacecraft subsystems via three power busses. The attitude control electronics (ACE) provided closed loop attitude control by processing sun sensor data and using electromagnetic torque rods to orient the spacecraft. The nominal orientation of SAMPEX pointed the solar arrays toward the sun and the instruments in the zenith direction. The telecommunications system consisted of two omnidirectional antennae and telecommunication electronics. The control of the spacecraft was managed through the Small Explorer Data System (SEDS), which consisted of the recorder/processor/packetizer (RPP), command telemetry terminal (CTT) and 1773 data bus. New technology utilized in the SEDS included a solid-state memory and an optical fiber data bus. The data processing unit (DPU) provided control for the science instruments which were mounted on the external surface of the spacecraft's structure. The instrument complement included the Low Energy Ion Composition Analyzer (LEICA), Heavy Ion Large Telescope (HILT), Mass Spectrometer Telescope (MAST), and the Proton/Electron Telescope (PET).

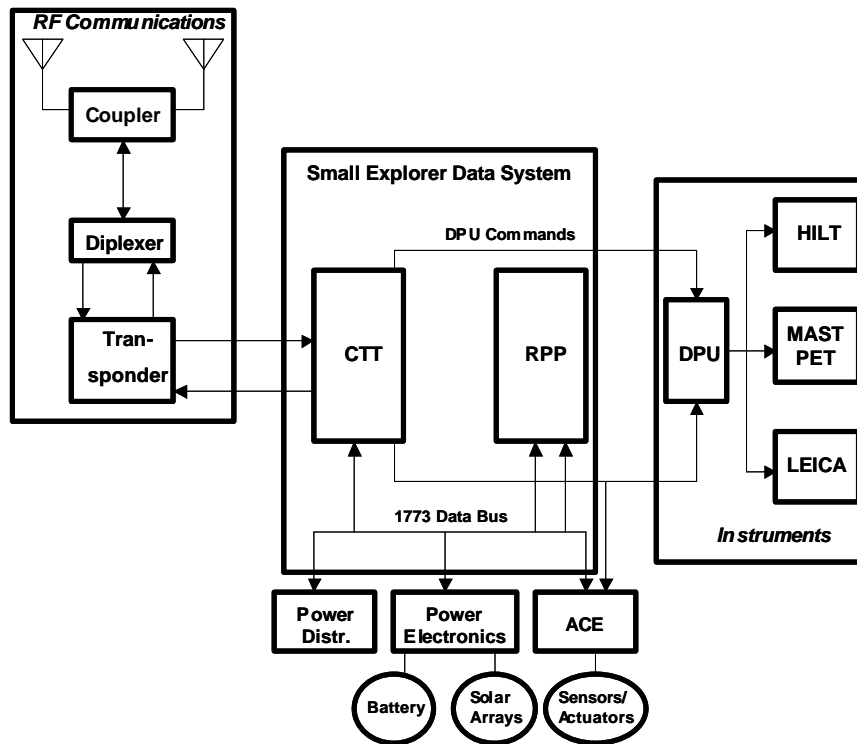


Figure 3.1.1.1-2 SAMPEX Spacecraft Architecture

The spacecraft was operated through an operations control center at NASA's Goddard Space Flight Center (GSFC) and commands were sent to the spacecraft once per day. Data from the instruments was recorded on-board and downlinked to the earth ground station twice per day. Science operations of SAMPEX were generally autonomous and did not require a great deal of interaction between the spacecraft and the ground.

3.1.1.2 SAMPEX DSM Analysis Results

The interface DSM for SAMPEX can be found in Figures 3.1.1.2-1. The clusters of components in the interface DSM correspond to the subsystems identified in the system architecture in Figure 3.1.1.1-2. The subsystem overlap in the matrix can be seen to very minimal.

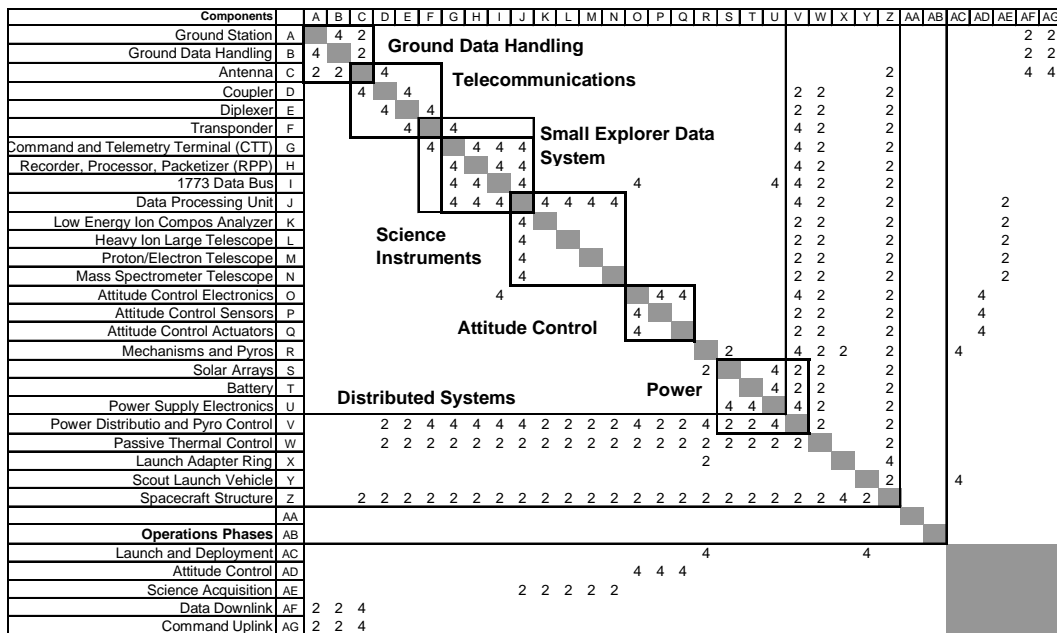


Figure 3.1.1.2-1 SAMPEX Interface DSM

The technology risk DSM for SAMPEX can be found in Figure 3.1.1.2-2. The components in the SEDS were assumed to have higher risk and were assigned higher TRF values since these elements utilized new technology that had been tested in a relevant Earth-environment, but not demonstrated in space. The methodology used to calculate values in the technology risk DSM, where new technology

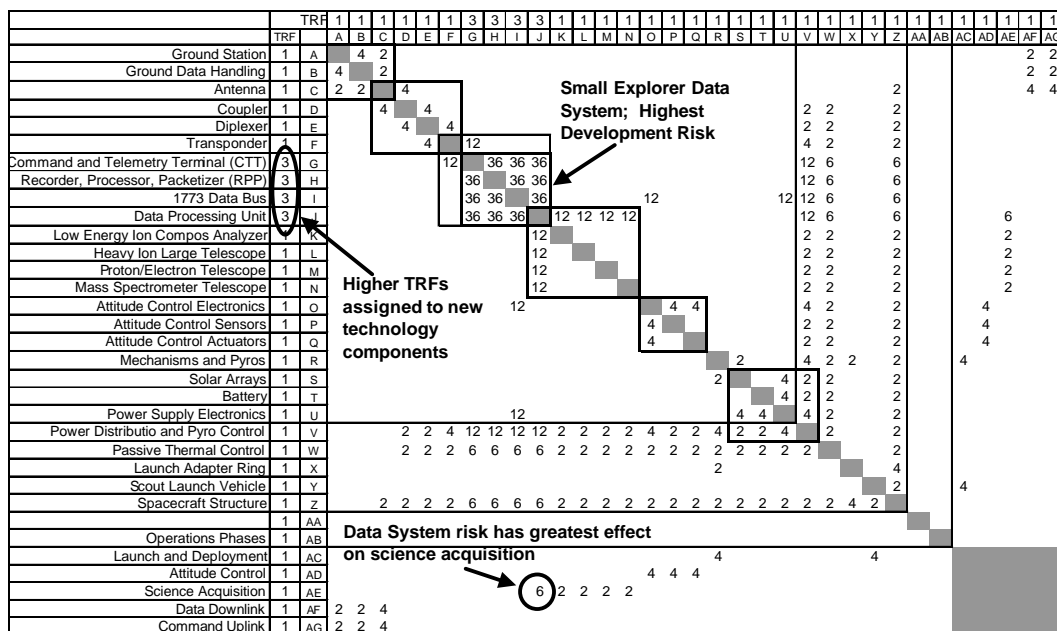


Figure 3.1.1.2-2 SAMPEX Technology Risk DSM

components are utilized together at an interface with high interdependence generates high values in the DSM. As seen in Figure 3.1.1.2-2, the large values in the technology risk DSM provide a visual representation that new technology is being used in an important interface in the spacecraft.

The technology risk DSM also highlights that the moderate risk of the SEDS components results in a moderate risk impact to science operations. The remainder of the components utilized on SAMPEX had flight heritage and thus the remainder of the technology risk DSM does not identify any other risk “hot spots.”

3.1.1.3 SAMPEX Lessons Learned Applicable to DSM Analysis

As the first in a series of missions in the SMEX Program, SAMPEX had to address its own project needs as well as those affecting later missions. Figueroa and Colón (1996) highlighted some of the approaches the SAMPEX Project took to be cost-effective and to lay groundwork necessary for future missions in the SMEX Program.

As an ongoing series of missions, the SMEX program was set up with both dedicated project organizations and shared project functions. The dedicated project functions included development of specific spacecraft subsystems, while shared functions included those associated with operations management, flight assurance, general project and institutional support, systems engineering and software. Figure 3.1.1.3-1 shows the major functions managed at both the Project and Program level.

The interface DSM shows the subsystems have little overlap, thus the subsystems lent themselves to somewhat independent development. In general the subsystem functions identified in Figure 3.1.1.3-1 are consistent with the clusters in the DSM and the SAMPEX project was successful in

developing and operating the spacecraft with this organization. Figueroa and Colón noted that the “concurrent engineering and the parallel development of components worked well.”¹⁴

The interface DSM also shows a fair amount of integration work required with respect to power, thermal, and structures. In addition to specific organizational leads for these functions, a systems engineer was responsible for integration. Since the integration functions and associated issues would have commonality to other SMEX missions, the systems engineering function was shared across SMEX’s multiple projects.

The major observation from the technology risk DSM was the collection of high-risk values associated with the SEDS components. The SEDS design was intended to provide a backbone for future SMEX spacecraft, so its flight on SAMPEX was serving as a risk mitigation strategy to validate the

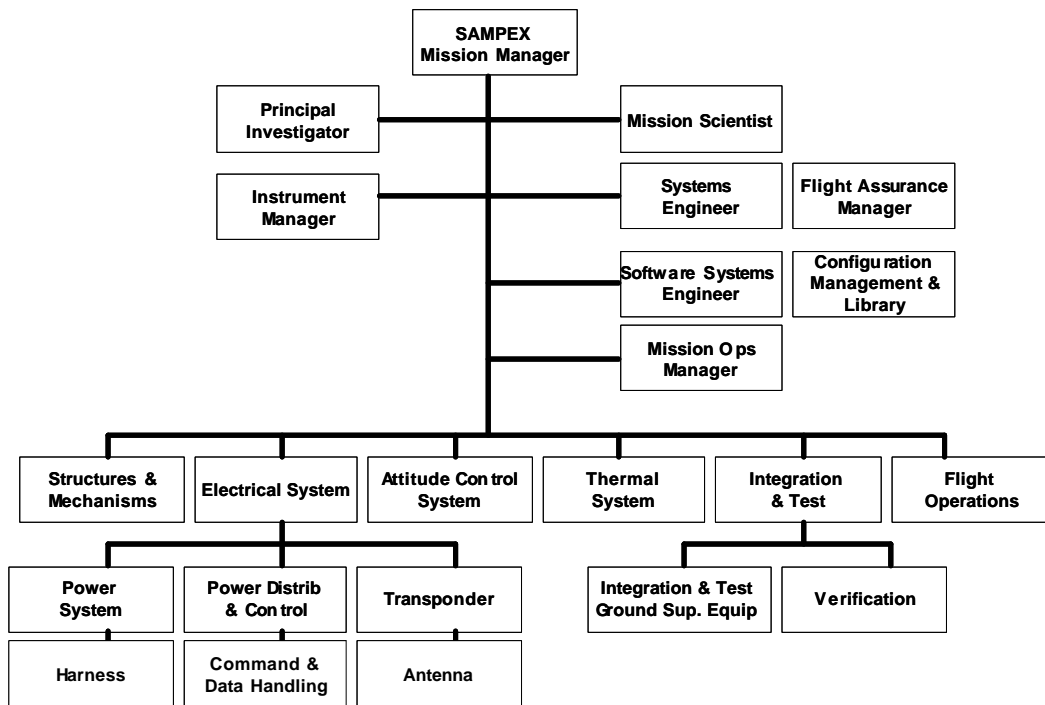


Figure 3.1.1.3-1 SAMPEX Project and SMEX Program Responsibilities

¹⁴ Figueroa and Colón (1996), p. 408.

SEDS design. An operational SEDS would enable future SMEX missions to be developed and integrated quickly and inexpensively. The SEDS use of standard data bus interfaces enabled the project team to use low-cost commercial equipment in a bench-top configuration to perform early development testing. The use of standard interfaces and protocols also meant the project was able to benefit from technology development of others and reduce development overhead. The SAMPEX project mitigated risk associated with the SEDS, the power system and attitude control electronics by utilizing an engineering test bed for an extensive verification of hardware and software.

In general, Figueroa and Colón also noted the importance of early project planning. Each mission in the SMEX Program was to take less than three years from the start of detailed design to launch. After a three-month definition phase, SAMPEX was able to design, develop and launch a unique spacecraft within 35 months. Obviously SAMPEX met the schedule goals, however the authors felt the detailed planning, end-to-end systems evaluation, and cost and risk assessment would have benefited from a longer definition period.

Although the interface and technology risk DSMs are fairly simple for a small spacecraft such as SAMPEX, they can provide a quick visualization of the degree of component independence or integrality and provide insight into the impact of choices made with respect to a component's technical maturity.

3.1.2 Case 2: Clementine

3.1.2.1 Clementine Mission and Spacecraft Description

The Clementine spacecraft and mission has been described in detail by Regeon, Chapman and Baugh (1995) and Horan and Berkowitz (1996). The Clementine spacecraft was launched on January 25, 1994 as technology demonstration mission with secondary objectives to study the surface of the Moon

and to flyby an asteroid.¹⁵ Developed by the Department of Defense (DoD) Ballistic Missile Defense Organization (BMDO), Clementine's primary objective was to evaluate the performance of lightweight components and sensors developed for the Strategic Defense Initiative Organization. Using the Moon and the asteroid as targets for the spacecraft, a secondary objective of the Mission was to provide data on these bodies to the scientific community. Clementine spent ten weeks taking images of the lunar surface, and one of its major discoveries was the detection of possible ice deposits near the lunar south pole. On May 4, 1994 Clementine left lunar orbit to fly by the asteroid 1620 Geographos. Shortly after leaving lunar orbit, the spacecraft was lost when its propellant was depleted due to a software error. During the shortened mission, Clementine achieved its primary objective by gathering performance data on the of the technology demonstration components.

The Clementine spacecraft, seen in its flight configuration in Figure 3.1.2.1-1, had a mass of 463

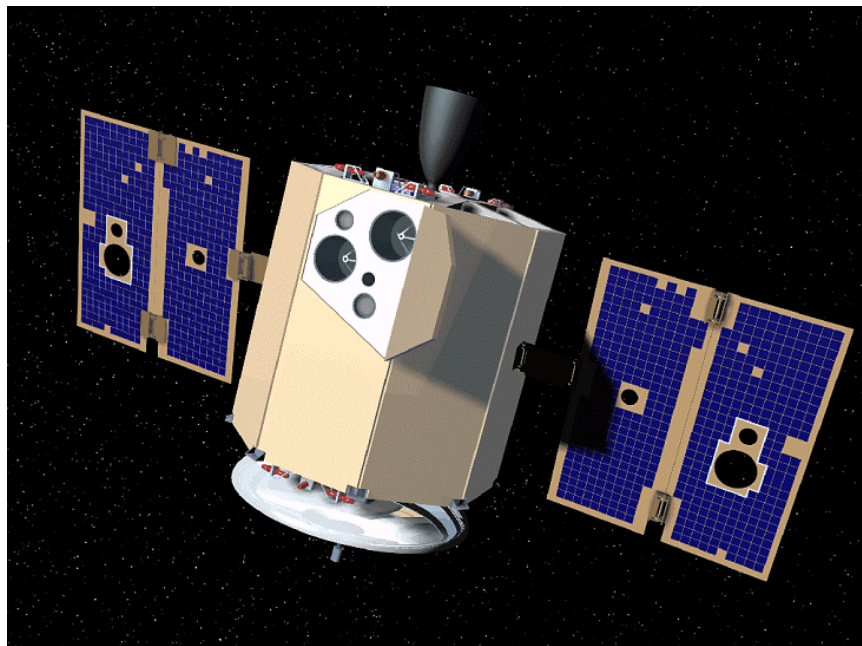


Figure 3.1.2.1-1 Clementine Spacecraft

¹⁵ Horan and Berkowitz (1996) noted two potential origins for the name of the spacecraft. "Some say that Clementine was an obvious name for the mission because, after the flyby of Giacobini-Zinner (asteroid), the spacecraft would be 'lost and gone forever,' as described by the well-known folk song. Others say that Clementine was an informal, unofficial, randomly-selected code word." Horan, Donald M. and Berkowitz, Bruce D., "Clementine," in *Reducing Space Mission Cost*, edited by Wertz, James R. and Larson, Wiley J., Space Technology Library, Microcosm Press, Torrance, CA, 1996, pp. 427-447.p. 430.

kg fully fuelled. The spacecraft was powered with two solar arrays capable of being gimbaled about a single axis. A lightweight nickel-metal-hydride battery provided for energy storage and a power distribution and control subsystem supplied power to the spacecraft subsystems. The attitude control subsystem utilized star cameras and inertial measurement units (IMUs) to sense spacecraft position. Reaction wheels provided for fine attitude control while monopropellant thrusters were used for large pointing maneuvers. The propulsion subsystem consisted of solid rocket motors for the large trans-lunar transfer injection (TTI) and bi-propellant thrusters for smaller velocity corrections. A command, telemetry, and data handling (CT&DH) subsystem processed uplink commands and downlink telemetry data, handled command and data handling of the instruments, and performed attitude data processing and spacecraft control. Communications with the ground utilized either a low-gain omni-directional antennae or a high-gain fixed-body parabolic antenna. The spacecraft maintained thermal control with thermostatically-controlled heaters, passive insulation and heat pipes.

3.1.2.2 Clementine DSM Analysis Results

Utilizing a system block diagram and spacecraft technical data from Regeon et al. (1995), an interface DSM for the Clementine mission was generated and can be seen in Figure 3.1.2.2-1. The DSM shows that the individual subsystems do not have a noticeable amount of interdependence, however there are a fair number of distributed systems requiring integration.

The flight heritage of the Clementine spacecraft components was described in the Committee on Planetary and Lunar Exploration's (1997) article documenting lessons learned from the Clementine project. The flight heritage information was utilized to assign TRFs to the spacecraft components, resulting in the technology risk DSM in Figure 3.1.2.2-2. The TRF column in this matrix shows higher risk values for the star tracker, IMUs, the battery, release mechanisms, sensors and processor components.

deficiency “may well have contributed to the ultimate demise of Clementine after the lunar portion of the mission had been completed.”¹⁷

The band of interface dependencies associated with the distributed systems in both DSMs indicates a relatively high degree of integration tasks that would be required for the Clementine architecture. Clementine’s management approach for the project was to utilize a small team which was given complete responsibility and authority from design and construction through launch and operation.

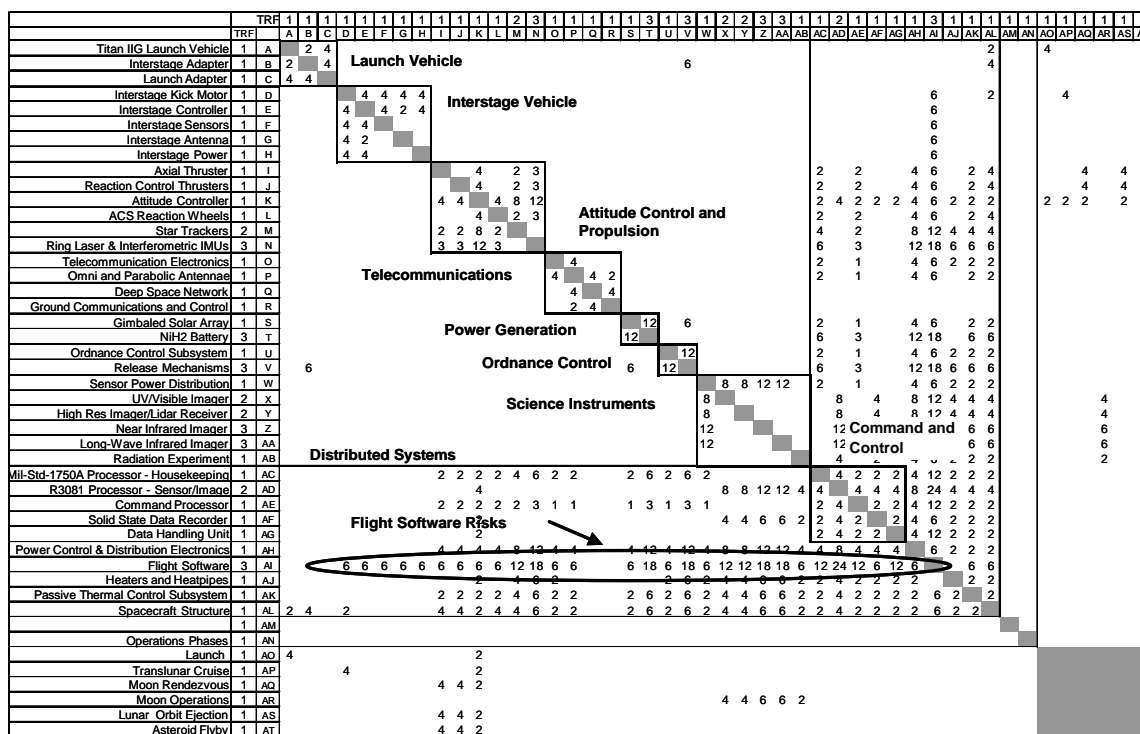


Figure 3.1.2.2-2 Clementine Technology Risk DSM

¹⁷ Ibid, Chapter 3.

3.2 Discovery Program

NASA's Discovery Program was set up in 1994 to provide the science community an opportunity to identify and implement smaller, faster programs to answer basic questions related to cosmic origin, evolution and destiny. Prior to Discovery, NASA's programmatic approach to planetary exploration was to identify specific mission objectives and then invite spacecraft manufacturers and the science community to bid on proposals to satisfy those objectives. In contrast, the Discovery Program solicited proposals for an entire mission – including the spacecraft and science objectives. “Rather than NASA determining what missions should be done, then inviting the science community to participate... we could instead solicit missions from the science community – who would propose to develop and operate whole missions themselves in consort with industry.”¹⁸ The goal of the program was to launch many smaller and faster missions to do focused science. The target cost for each of these missions was less than \$299 million.¹⁹

As of late 2001 eight missions have been selected for the Discovery program, five of which have been launched. The missions and a brief description of their primary objectives can be found in Table 3.2-1. The first two Discovery Missions, NEAR and Mars Pathfinder, were selected as case studies because of extensive information available related to the spacecraft architecture, the project organizational approach and the selection of technology used.

¹⁸ Huntress, Wesley T. Jr., “The Discovery Program,” *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 207-213, 1999, p. 210.

¹⁹ <http://discovery.jpl.nasa.gov/overview.html>

Table 3.2-1 – Discovery Program Missions

Mission	Launch Date	Primary Objective
Near Earth Asteroid Rendezvous (NEAR)	17 February 1996	Asteroid 433 Eros Orbiter
Mars Pathfinder	4 December 1996	Mars surface lander and rover
Lunar Prospector	7 January 1998	Lunar orbiter
Stardust	7 February 1999	Comet P/Wild 2 coma sample return
Genesis	8 August 2001	Solar wind sample return mission
Comet Nucleus Tour (CONTOUR)	July 2002*	Mission to fly by three comet nuclei
Deep Impact	January 2004*	Mission to Comet Tempel 1
Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER)	March 2004*	Mission to orbit Mercury

*Planned launch date at time of writing

3.2.1 Case 3: Mars Pathfinder

3.2.1.1 Mars Pathfinder Mission and Spacecraft Description

Mars Pathfinder served as both a technology demonstration mission and a science mission. The technology mission objectives were to demonstrate “a simple, reliable, and low cost system for placing science payloads on the surface of Mars,” and to demonstrate the mobility and usefulness of a microrover on the surface. The science objectives were to study the Martian atmosphere, the elemental composition of rocks and soil, investigate surface geology and to acquire surface meteorological data. (Muirhead 1996)

The Pathfinder achieved these objectives through a dramatic mission profile. The spacecraft was launched on a Delta II launch vehicle on December 4, 1996 on a seven-month cruise to Mars via a direct trajectory into the Martian atmosphere. The flight system consisted of three major elements – a cruise stage, the entry vehicle, and the lander.

On July 4, 1997, shortly before entering the Martian atmosphere, the cruise stage was jettisoned and the entry, descent and landing (EDL) sequence began. The EDL sequence is depicted in Figure 3.2.1.1-1.²⁰ The aeroshell, including heatshield and backshell, provided protection for the spacecraft during atmospheric entry. At about 9 km above the surface, the parachute (attached to the backshell) was deployed. Shortly after the parachute was deployed, the heatshield was jettisoned, the lander's attachment to the backshell was extended via a bridle, and landing radar was activated. At less than one-half kilometer above the surface, airbags surrounding the lander were inflated and solid rockets were fired to slow descent. About 15 meters above the surface, the bridle was cut dropping the airbag-cushioned lander to the surface. Once on the ground, the airbags were deflated and landing petals were deployed in a sequence to right the lander on the surface. The configuration of the lander on the surface is shown in Figure 3.2.1.1-2.²¹

A detailed description of the Pathfinder flight systems, including a system block diagram, can be

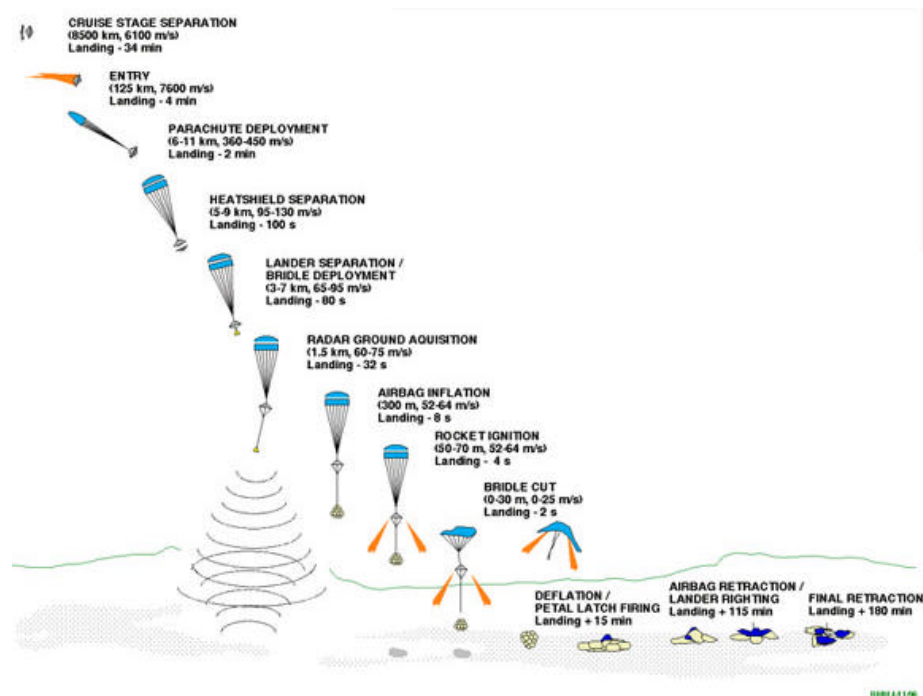


Figure 3.2.1.1-1 Mars Pathfinder Entry, Descent and Landing Sequence

²⁰ Figure from <http://mars.jpl.nasa.gov/MPF/>.

²¹ Figure from: <http://mars.jpl.nasa.gov/MPF/>.

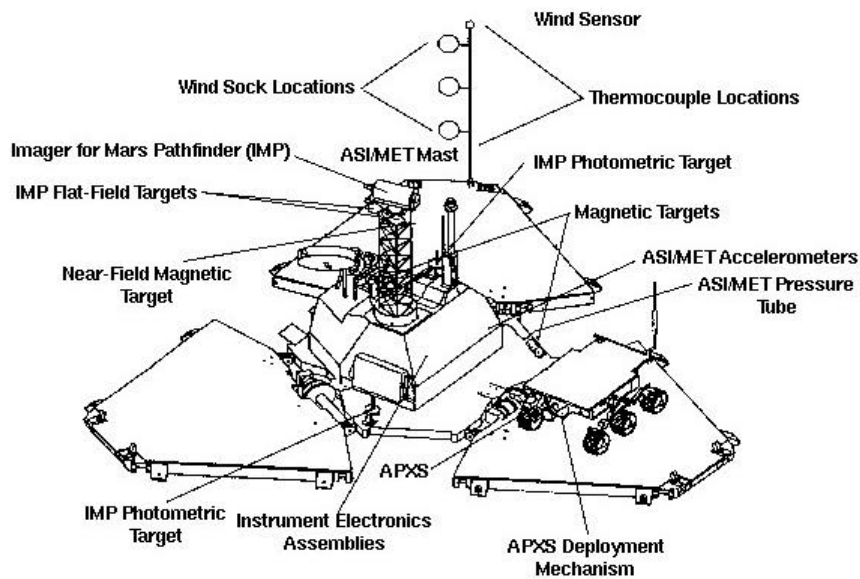


Figure 3.2.1.1-2 Mars Pathfinder Lander Configuration

found in Muirhead (1996). The flight system was made up of six major subsystems: Attitude and Information Management (AIM), Power and Pyrotechnic Switching (PPS), Telecommunications, Propulsion, EDL, and Mechanical Integration Hardware. Some of the major features of these subsystems are described below.

- The AIM combined the functions of attitude and articulation control and command and data handling into a single subsystem. Major flight systems connected to the central computer via an electronic chassis (VME backplane) and 1553 data bus. The lander and cruise vehicles had separate engineering processors for analog and digital measurement acquisition and multiplexing.
- The PPS took power from the solar arrays on the cruise stage or lander and supplied regulated voltage via the power bus. The pyrotechnic switching electronics use relays which were commanded from AIM.
- The Telecommunications subsystem consisted of the electronics and antennae. Separate low gain and medium gain antennae were used for cruise, EDL, and surface communications. A high gain antenna operated only on the surface of Mars.

- The Propulsion subsystem utilized mono-propellant hydrazine and eight small thrusters.
- The EDL subsystem, utilized in the EDL operations described earlier, consisted of the aeroshell, parachute, solid rocket assisted decelerator, bridle, radar altimeter, and airbags.
- The Mechanical Integration Hardware consisted of the cruise and lander mechanical structures as well as other hardware such as the actuators to drive the lander petals.
- Science instrumentation included the Sojourner Rover and its ultra high frequency (UHF) communication link, an imager and the Atmospheric Structure Instrument (ASI). The Rover carried an imager and an Alpha Proton X-ray Spectrometer (APXS). The APXS had capability to determine elemental chemistry of surface materials. The ASI had temperature, pressure and wind sensors and provided atmospheric data during descent and obtained meteorology data during landed operations.

3.2.1.2 Mars Pathfinder DSM Analysis Results

An unclustered component DSM (Figure 3.2.1.2-1) was created for the Pathfinder using the six

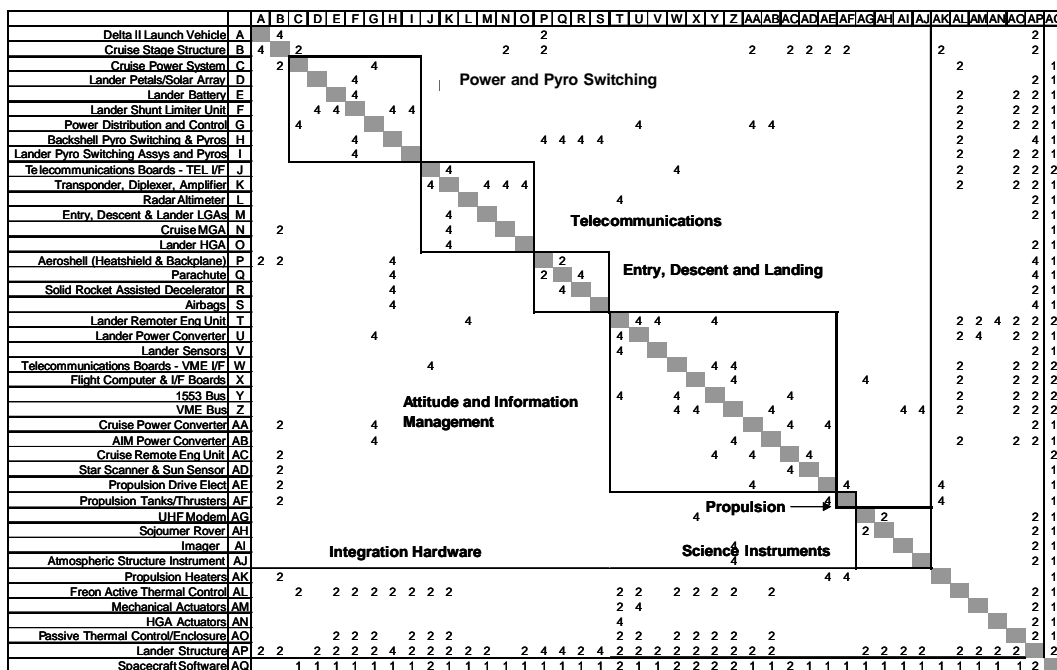


Figure 3.2.1.2-1 Component DSM for Pathfinder – JPL Subsystem Grouping

major flight systems of Pathfinder described by Muirhead (1996). The matrix shows that the six subsystems selected have captured a majority of the interface dependencies. However a few interfaces related to the backshell pyrotechnic switching and power distribution are not included in a cluster. The matrix also shows the distributed systems and integration hardware interface with a majority of the components.

The initial Pathfinder interface DSM was clustered via the process described in Section 2.2.3. The clustered interface DSM for the Mars Pathfinder can be found in Figure 3.2.1.2-2. The matrix shows a natural grouping of components with highly dependent interfaces. These clusters represent spacecraft subsystems such as propulsion, telecommunications and the EDL subsystem. There is some overlap in

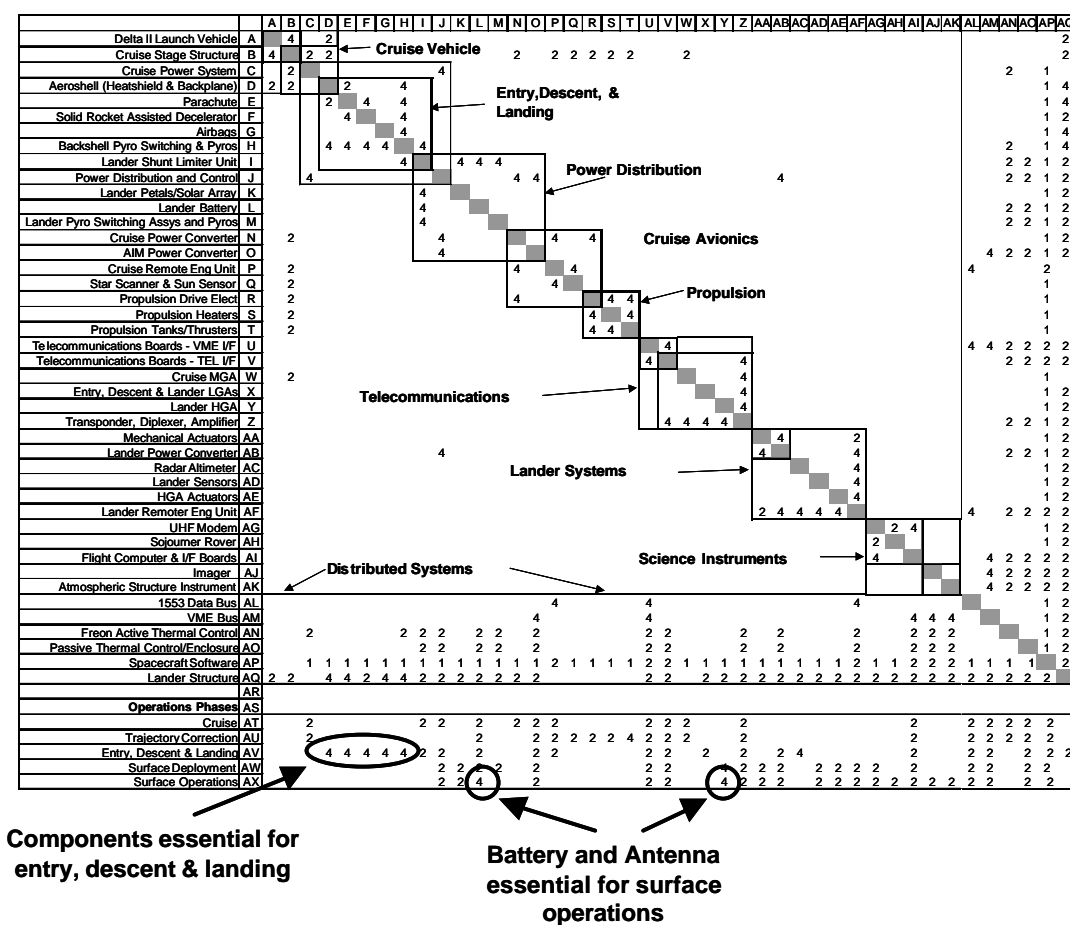


Figure 3.2.1.2-2 Mars Pathfinder Interface DSM

subsystem elements. For instance, the EDL overlaps the cruise vehicle primarily because the aeroshell serves as a structural for both elements. The power distribution system shows overlap with the entry vehicle and cruise vehicle systems. Also, the propulsion system shows some overlap with the attitude control systems in the cruise avionics, since these elements are essential for directing the spacecraft on a proper trajectory. There are also several distributed systems that interface with a large number of the components in the spacecraft. In general, the component portions of the matrix identify a fair number of specific clusters that must be integrated for successful operations.

The operations portion of the interface matrix can be used to identify some of the essential elements required for specific operations. For example, in the Entry, Descent and Landing operations phase, all of the components required for successful landing – aeroshell, parachute, radar, solid rocket assist motor, and airbags – are identified with a value of “4” indicating those components are essential for the operation. In the surface operations phase, the battery and lander high gain antenna were identified as essential components for this operations phase.

The technology risk DSM can be found in Figure 3.2.1.2-3. The matrix can be used to highlight areas of development and operational risk. One of the major objectives of the Pathfinder mission was to demonstrate new technologies that could help reduce the cost of delivering science instruments to Mars, thus along the TRF column, several components are identified with moderate levels of technology risk. These components included a radiation-hardened computer based on a commercial IBM computer, utilization of distributed processors linked together with a data bus, and components that supported the strategy for entry, descent and landing. Based on the detailed component information provided (Muirhead 1996, Muirhead 1997), TRFs were assigned using the criteria established in Table 2.2.2-1.

The resulting technology risk DSM identifies several clusters of technology risk areas. Not surprisingly, the EDL subsystem shows up as an area of high technology risk. The high values result from a set of interfaces identified with relatively high dependence between components with high technology risk. The interfaces associated with the central computer, distributed processors and data bus also had high technology risk values.

(1999) included lessons they learned during the development, testing and operations of Pathfinder, and those insights that relate somewhat to the interface and technology risk DSM will be discussed.

Depth of Technical Knowledge

The Pathfinder management felt project and subsystem managers' "in-depth technical understanding and knowledge of programmatic resources and design margins at all levels allowed for rapid decision making, saving time and money."²² The interface DSM analysis described in this work provided visibility to highly interdependent interfaces in the Pathfinder project. In future projects, the interface DSM could be used to help project personnel identify key areas where detailed technical knowledge may be necessary for management of the project or a particular subsystem.

The team carefully flowed down requirements from mission to system to subsystem, and thoroughly documented compliance through analysis, simulation, and test. "We never finished verification and checking, always striving towards a deeper understanding of System performance in the expected environment."²³ The developers became spacecraft operators and the in-depth knowledge they gained about the subsystems was key to the Pathfinder success. The success of the developer-operator strategy used in Mars Pathfinder identified a gap in the proposed DSM analysis framework. In their current form, the DSMs do not identify or quantify the dependency for knowledge about subsystems and components which would be required to operate them during critical operations phases. A third DSM, established to identify the degree of element knowledge required for an operational phase, could help to identify potential issues and risks during operational phases when the hardware responsibility shifts from developer to operator.

²² Muirhead, Brian K., "Mars Pathfinder Flight System Design and Implementation," *1996 IEEE Aerospace Applications Conference Proceedings*, Vol. 2, pp. 159 -171, 1996, p. 168.

²³ Spear, Anthony J., "Mars Pathfinder's Lessons Learned from the Mars Pathfinder Project Manager's Perspective and the Future Road," *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 235-247, 1999, p. 239.

Organization

The interface and technology risk DSMs identified a large number of component-to-component and component-to-operation interfaces which highlighted the depth of information exchange required for the project. The Pathfinder team inherently understood this requirement for information exchange in the project and used co-location to mitigate the problems associated with dealing with a large number of highly dependent interfaces and to insure efficient communication. “A flat organization structure and the co-location of management, systems, AIM, ground data system and mission operations have led to excellent communication and rapid problem resolution.”²⁴ The Pathfinder team’s strategy for organization was aligned with the project requirements for information flow.

Risk Identification and Mitigation

“Risk Management is essential. Never stop doing risk management.”²⁵ The Pathfinder program performed an early investigation on the nature and potential for development risk for each subsystem. These investigations were used to establish a plan with sufficient cost reserves and to balance the risk among all project elements. The mission risk was also assessed by breaking the mission phases into more detailed elements, creating an overall understanding to balance risk across all mission phases. “To no one’s surprise, the EDL phase emerged as the biggest Mission risk, with the airbags as the most risky EDL element.”²⁶ These observations are consistent with the patterns of high-risk numbers in the technology risk DSM. The project team utilized other methods to identify their risk areas and when identified, cost and schedule reserves were allocated.

The Pathfinder project seemed to have a good early understanding of the critical interfaces of the spacecraft and the team gave early focus to the Interface Control Documents (ICDs). However, Muirhead

²⁴ Muirhead (1996), p. 168.

²⁵ Spear (1999), p. 240.

²⁶ Spear (1999), p. 241.

noted the early attention to interfaces still did not mitigate development problems. In a rapid development project, “a near constant cycle of progress-problem resolution-progress cuts across many subsystems in a highly integrated design like Pathfinder’s.”²⁷ Further analysis could compare the relationship between the areas of high rework in Pathfinder to clusters of high risk in the technology risk DSM. It would be interesting to determine if the technology risk DSM could provide some insight as to where high rework potential exists.

Pathfinder recognized the simple, rapid development approach of the project had technical risk and employed a strategy for early integrated testing. They insured that a sufficient amount of hardware was available for test and the schedule was driven to permit early integrated testing. The spacecraft began assembly, test and launch operations (ALTO) testing 18 months prior to launch. Six major system tests were performed, each successive test with higher degrees of fidelity in hardware and software representing various spacecraft operating phases. The early integrated testing was valuable in helping to refine changes in flight software. The EDL component tests, which could not be tested in the ALTO configuration, underwent a parallel qualification test program.

Muirhead also noted that the program held reserves for “unpredictable risk.” They found mass growth to be a problem due to “unknowns in the EDL development, particularly the airbags.”²⁸ The initial budget reserve of 40% and schedule reserve of 20 weeks permitted the project team to address the unexpected activities associated with this subsystem. The extremely high technology risk values in the EDL area correlated to an area in the Pathfinder program where budget and schedule reserves were used. The technology risk DSM has potential to identify an area where unpredicted activities would be required and could be used to justify budget and schedule reserves.

²⁷ Muirhead (1996), p. 169.

²⁸ Muirhead (1996), p. 170.

3.2.2 Case 4: Near Earth Asteroid Rendezvous

3.2.2.1 NEAR Mission and Spacecraft Description

The NEAR science mission was the first launch in NASA's Discovery Program. NEAR was launched in February 1996 to provide the first "comprehensive picture of the physical geology, composition, and geophysics of an asteroid."²⁹ NEAR's mission extended over four years and included a flyby of Comet Mathilde, an initial flyby of Comet Eros, a final rendezvous with Eros which included a detailed study of the asteroid for over a year. All of NEAR's objectives were achieved with great success. Figure 3.2.2.1-1³⁰ provides an overview of the NEAR mission.

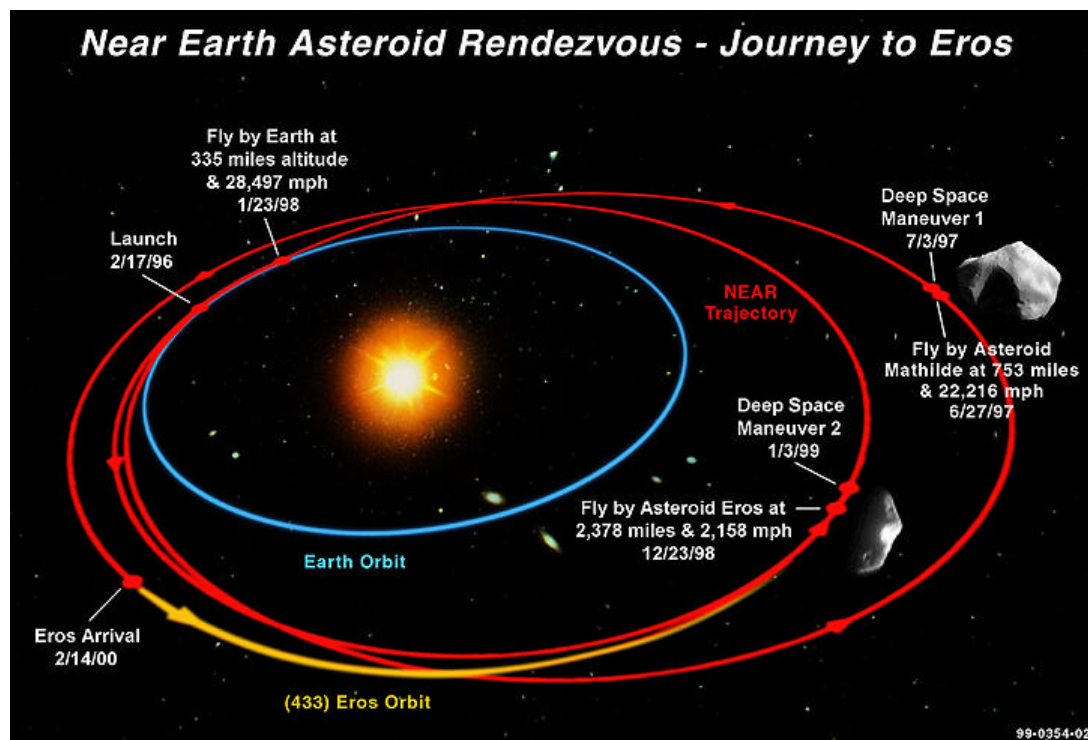


Figure 3.2.2.1-1 NEAR Mission Overview

²⁹ Johns Hopkins University Applied Physics Laboratory, "Near Earth Asteroid Rendezvous – A Guide to the Mission, the Spacecraft, and the People," <http://near.jhuapl.edu>, December 1999.

³⁰ Figure from <http://near.jhuapl.edu>.

Following the accomplishment of its primary mission to map Eros, a bold plan to land the spacecraft on the surface of Eros was implemented. Although not designed for this task, NEAR touched down gently on the surface, taking 69 close-up pictures of the asteroid until its landing.³¹

The NEAR Spacecraft has been described in detail by Santo, Lee and Cheng (1996). The NEAR mission trajectory was selected such that the Sun-spacecraft-Earth angle was always less than 40 degrees except after the first month of launch and during the two months following earth flyby. Using this mission profile, the spacecraft designers were able to reduce the spacecraft complexity by using a fixed high gain antenna, fixed solar panels, and fixed science instruments. The mission design provided enough on-board propellant to orient the entire spacecraft to meet instrument observation, solar power generation and communication requirements.

The spacecraft was designed with two independent structures: the propulsion system and the spacecraft. This design approach permitted a clean interface definition and allowed for independent design and test capability for the two major elements. This architecture created a weight penalty in exchange for a clean and simple interface. Johns Hopkins University's (JHU's) Applied Physics Laboratory (APL) designed and fabricated the spacecraft, while Aerojet built the propulsion system.

Figure 3.2.2.1-2 shows the NEAR spacecraft in its flight configuration.³² Four solar panels were deployed after launch. A parabolic antenna was located on the forward deck and the science instruments were mounted to the aft deck. The propulsion system was mounted between the two decks with a 100-lb (450 N) thruster located along the center of mass in an orientation that permitted solar panels to face the sun during all large maneuvers. Eight side panels provided structural support between the forward and aft decks. On the aft deck, the science instruments were located around a structural spacecraft adapter, which also provided a physical interface to the Delta launch booster.

³¹ <http://www.jhuapl.edu/public/pr/010214.htm>

³² Figure from <http://near.jhuapl.edu>.

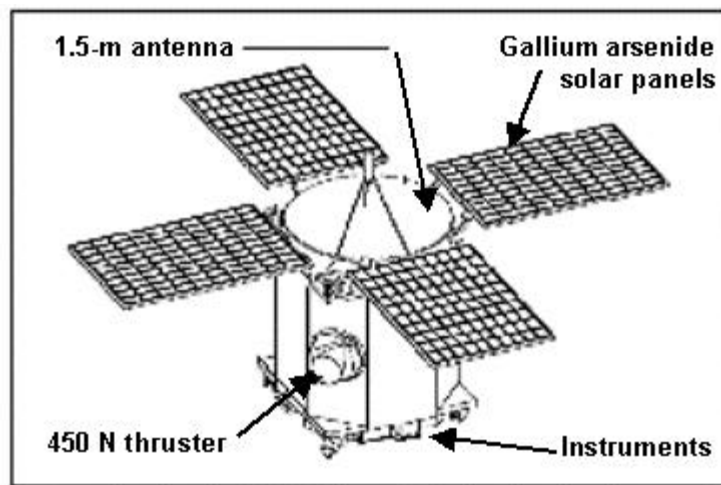


Figure 3.2.2.1-2 NEAR Spacecraft Flight Configuration

The spacecraft was designed with a distributed architecture where subsystems do not share common hardware. The major subsystems included guidance and control (G&C), telecommunications, command and data handling (C&DH), propulsion, power and science instrumentation. Seven processors were distributed among the C&DH, G&C, and science instruments and were interfaced together utilizing a standard 1553 data bus. Some of the major features of the spacecraft subsystems are highlighted below.

- G&C contained all the sensors and actuators necessary for attitude control. The attitude sensors included sun sensors, star tracker, and IMU. The actuators included the reaction wheels and propulsion subsystem thrusters.
- Telecommunications coverage was provided through a 1.5 m high gain dish antenna as well as two low gain antennae.
- C&DH consisted of redundant processors, solid-state recorders, power switching and an interface to the 1553 data bus.
- The propulsion system consisted of tanks, one large bi-propellant thruster and 11 smaller monopropellant thrusters.
- The power system, with solar arrays, battery, and control electronics, was designed to meet spacecraft needs at both warm operating conditions and at the farthest distance to the sun. Power to spacecraft equipment was supplied through a regulated power bus.

flight-proven hardware. The parallel development required highly decoupled development activities and the interface DSM shows a pattern of independent subsystems. The project put forth a great effort to maintain the independence. For example, the project made a decision to decouple the propulsion and spacecraft structures. “This design simplified the analysis and the testing and (the) interface between the subcontractor and APL.”³³

The case study also described APL’s use of a matrix organization to complete the project. APL had a successful history of running projects in this manner and it was also a successful approach for NEAR. The subsystem leads came from the organization’s technical discipline skill centers. The organizational approach appears to have been well aligned with project architecture. With highly decoupled subsystems, the interface dependencies across subsystems is minimized and the development teams would be able to perform a great deal of work within their respective skill centers. All of the work was not decoupled however, as noted in the large number of distributed system interfaces. The coordination of these integration activities fell under a systems engineering lead. To further support integration all major project participants met weekly which provided an opportunity to identify systems level and integration issues.

The relatively low values in the technology risk matrix are consistent with the project philosophy to utilize components with flight heritage. “On NEAR, the rule was if you could get it off the shelf, this is what would be done.”³⁴ This strategy was important for meeting the target launch date and enabled the project to get mature hardware delivered quickly. With mature technology, the case study noted that the project did not hold contingency funding at the project level. This strategy would have been difficult to employ if not for the mature flight heritage of many of the key components in the system.

³³ Kleiner, Brian M. and Newcomb, John F., “NEAR, Rendezvous with Faster, Better, Cheaper NASA Projects,” Case Study written for NASA Academy of Program and Project Leadership, <http://appl.nasa.gov>, 1997, p. 18. The authors also noted that an important element to the success of this strategy was having adequate design margin to absorb the weight penalty.

³⁴ Ibid. p. 10.

3.2.2.4 Final Comments on Mars Pathfinder and NEAR

In future projects, the DSM analysis tool could be useful in identifying whether or not the interface dependencies in the system architecture really support the project management implementation strategy. Both NEAR and Pathfinder demonstrated successful completion of highly complex technical achievements within a very short development time, but the implementation approaches were vastly different. In the NEAR case, the DSM analysis tool demonstrated an ability to clearly identify the subsystem independence and technical maturity. Decoupled subsystems can support the desire for parallel development efforts and low technology risk can enable project managers to reduce the levels of project reserves. In contrast, the Mars Pathfinder case showed a large number of interdependent subsystems and the objective as a technology demonstration mission meant inherently higher technology risk. In contrast to NEAR, the Pathfinder team collocated key subsystems to enhance systems integration. Further, the technical immaturity of some of the components selected established the need for project reserves to handle unplanned, but not entirely unexpected rework activities.

3.3 Mars Surveyor Program

The Mars Surveyor Program was established in 1993 to build knowledge about Mars through an ongoing series of small spacecraft missions. The program was designed to take advantage of the favorable alignment of the two planets which occurs about every 26 months. The first mission of the program was Mars Global Surveyor, which met the 1996 Mars launch opportunity. In 1995, the Mars Surveyor '98 program was formed to develop the MCO and MPL to meet the late 1998/early 1999 launch opportunity. These three projects conducted under the Mars Surveyor Program have been included as case studies for the DSM analysis. Table 4.2-1 provides a brief timeline and status of these three Mars Surveyor missions.

Table 4.2-1 – Mars Surveyor Projects included in Case Studies

Mission	Launch Date	Mars Arrival Date	Status
Mars Global Surveyor	Nov. 7, 1996	Sep. 12, 1997	Achieved primary mission objectives; Spacecraft still operating in Mars orbit
Mars Climate Orbiter	Dec. 11, 1998	Sep. 23, 1999	Lost during entry into Martian atmosphere
Mars Polar Lander	Jan. 3, 1999	Dec 3, 1999	Lost during entry into Martian atmosphere

3.3.1 Case 5: Mars Global Surveyor

3.3.1.1 MGS Mission and Spacecraft Description

The MGS was designed to recover some of the science objectives from the 1993 loss of the Mars Observer spacecraft. The spacecraft utilized spare electronic assemblies and other parts from the Mars Observer program. The mission objectives included high resolution imaging of the surface and studies of

topology, gravity, magnetic fields, atmosphere, weather and climate.³⁵ The spacecraft can be seen in its mapping configuration Figure 3.3.1.1-1.³⁶ The MGS science payload used to perform these studies consisted of the Magnetometer/Electron Reflectometer, Mars Orbit Camera, Mars Orbit Laser Altimeter, Thermal Emission Spectrometer, a radio science experiment, and a system to assist in relaying information from future landed vehicles.

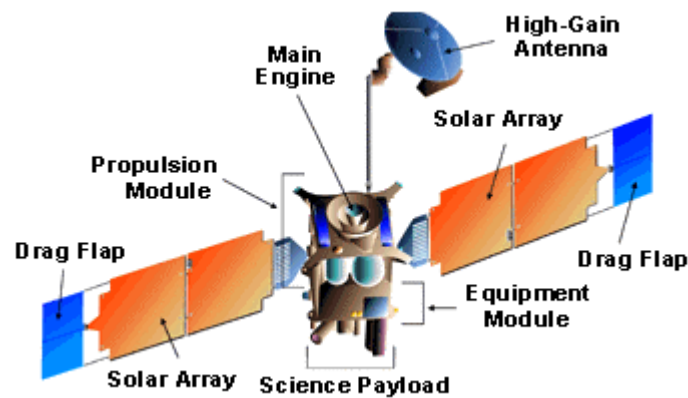


Figure 3.3.1.1-1 MGS Spacecraft – Orbiter Configuration

The MGS spacecraft was divided into four sub-assemblies known as the equipment module, the propulsion module, the solar array support structure, and the high gain antenna support structure. The equipment module housed the avionics packages and science instruments. With the exception of the Magnetometer, all of the science instruments were attached to the nadir equipment deck. The propulsion module contained the propellant tanks, main engines, and attitude control thrusters and served as the structural interface to the launch vehicle. Two solar arrays were mounted to the spacecraft and provided two major functions – electrical power generation and following capture into Mars orbit the arrays were used as aerobrakes to slowly lower the spacecraft to the mapping orbit. Lockheed Martin Astronautics

³⁵ Detailed information about the MGS mission and the spacecraft can be found at <http://mars.jpl.nasa.gov/mgs> and from Dallas, S. Sam, "Mars Global Surveyor Mission," 1997 IEEE Aerospace Conference, Snowmass at Aspen, CO, Feb. 1-8, 1997, pp. 173-179 of Proceedings.

³⁶ MGS spacecraft figure from <http://mars.jpl.nasa.gov/mgs/>

the degree of its maturity will impact the risk of the critical propulsion operations. The importance of the solar array to the aerobraking operations can also be seen in the matrix.

3.3.1.3 MGS Lessons Learned Applicable to the DSM Analysis

JPL was responsible for the overall MGS mission, with LMA in Denver, Colorado responsible for design, build and test of the spacecraft. The Mars Surveyor Operations Project was responsible for the operations of the MGS as well as future Mars Surveyor spacecraft. Further study of the detailed subsystem and integration responsibilities would be of interest to compare to the patterns in both the interface and technology risk DSMs. In particular, since MGS was successful it would be interesting to relate what strategies were used to facilitate information exchange between the three organizations with major MGS responsibilities.

Although the mission was designed to be technically mature utilizing a number of spare parts from the Mars Observer Program, there were some developmental and operational risk areas as pointed above in the technology risk DSM. The MGS project had to mitigate these development risks through a ground test program.

3.3.2 Cases 6 and 7: Mars Surveyor 1998– Mars Climate Orbiter and Mars Polar Lander

The Mars Surveyor Project '98 was established by NASA's JPL to define, design, develop, test, integrate and operate the MCO and MPL. The missions and the MCO and MPL spacecraft are described below.

3.3.2.1 Mars Surveyor '98 Mission and Spacecraft Description

3.3.2.1.1 MCO Mission and Spacecraft Description

The MCO was established with two primary objectives. First, MCO was to act as a Martian weather satellite, conducting science studies for one Martian year (about two Earth years). Two science instruments, the Pressure Modulator Infrared Radiometer (PMIRR) and Mars Color Imager (MARCI) were designed to provide detailed information on the atmospheric composition and climate. Secondly, MCO was to act as a relay station to transmit signals from the MPL via a UHF relay system.

The MCO spacecraft can be seen in Figure 3.3.2.1.1-1.³⁷ Once separated from the Delta 7425

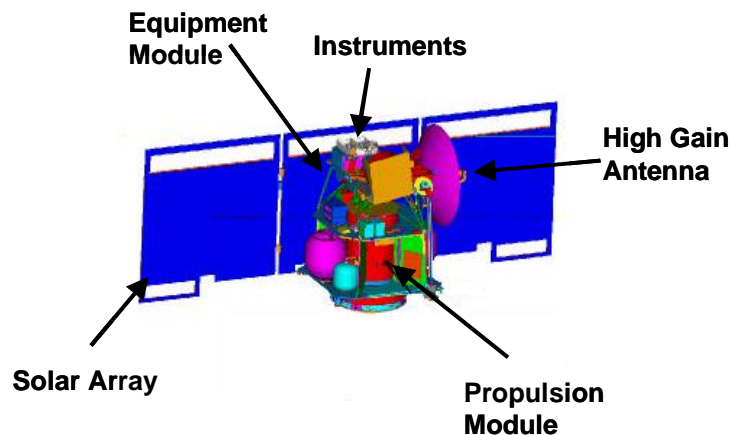


Figure 3.3.2.1.1-1 – MCO Spacecraft Orbiter Configuration

³⁷ Figure from <http://mars.jpl.nasa.gov/msp98/orbiter/>.

launch vehicle, the solar arrays and high gain antenna (HGA) deployed. The spacecraft had two primary structures: the propulsion module and the equipment module. The science instruments and UHF antenna were attached to the equipment module which would be nadir-facing during mapping operations.

Upon arrival at Mars, the MCO was intended to be propulsively inserted into a highly elliptical orbit. Once captured, the spacecraft's orbit would be slowly lowered over two months using the solar arrays as an aerobrake.

Contact was lost with the MCO during the Mars orbit insertion maneuver on September 23, 1999. Subsequent investigation by the MCO Mishap Investigation Board (MIB) found the MCO was put into an orbit too low for spacecraft survival. The MIB found that MCO was placed into the wrong orbit because information used to calculate trajectory corrections contained data in English units rather than the expected metric units.³⁸

3.3.2.1.2 MPL Mission and Spacecraft Description

The MPL's mission was designed to explore the surface of Mars' polar region for near-surface ice, evidence of cyclic climate change, and to characterize the seasonal cycles for water, carbon dioxide, and dust. The primary science instruments included the Mars Volatiles and Climate Surveyor (MVACS) instrument and the Light Detection And Ranging (LIDAR) instrument. The lander also carried the Mars Descent Imager (MARDI) to take detailed images during the descent and landing. The MPL had a UHF link for communication with the MCO as well as a direct-to-earth link. The MPL also carried two basketball-sized microprobes for release during entry into the Martian atmosphere. These probes, also known as Deep Space 2 (DS-2), were designed to withstand high velocity impact and penetrate the

³⁸ Mars Climate Orbiter Mishap Investigation Board, "Mars Climate Orbiter Mishap Investigation Board Phase I Report," November 10, 1999, p. 13.

surface. These miniature probes were intended to take atmospheric data during descent to the surface and, after impact, to collect and analyze a subsurface soil samples.

The MPL was a three-in-one spacecraft: an interplanetary cruise vehicle, a Martian entry vehicle, and a lander. The major elements of the MPL were a cruise structure, the aeroshell, and the lander. The cruise stage had its own solar arrays, to generate power during the interplanetary trip to Mars as well as attitude control sensors and telecommunications equipment. The two DS-2 microprobes were physically attached to the cruise stage. The lander was located in the aeroshell (backshell and heatshield) during cruise and the early part of entry. Equipment used for both the cruise and landing phase, such as avionics, were located in a thermal enclosure on the lander. Figure 3.3.2.1.2-1 shows the major elements of the MPL in both the cruise and lander configuration.³⁹

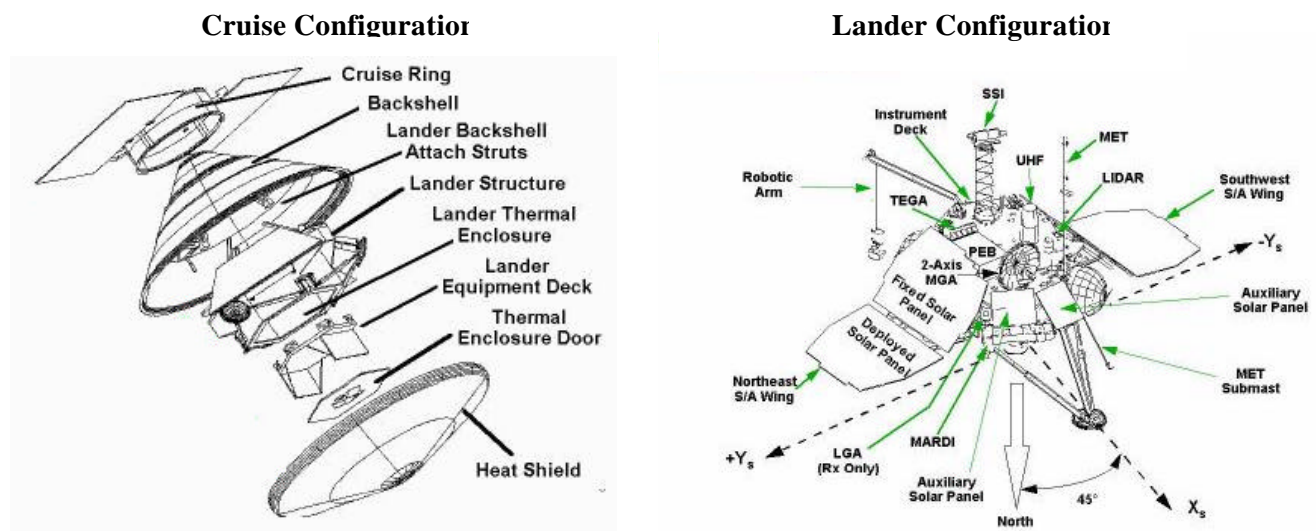


Figure 3.3.2.1.2-1 – Mars Polar Lander: Flight and Landed Configurations

The MPL traveled to Mars on a direct trajectory. The sequence of events for entry, descent and landing was planned as follows. Once the spacecraft was in the proper orientation and just before entry into the atmosphere, the cruise stage and DS-2 microprobes were jettisoned. During entry, the lander was

³⁹ Figures from: <http://mars.jpl.nasa.gov/msp98/lander/>.

designed to be protected from heating by the aeroshell. About 8 km from the surface the parachute was to be deployed from the backshell and the heat shield released. At approximately 1.5 km above the Martian surface the lander was to be released from the parachute and backshell, permitting the lander to continue to the surface under powered-descent. This sequence of events is illustrated in Figure 3.3.2.1.2-2.

On December 3, 1999 contact was lost with the MPL as it was scheduled to enter the Martian atmosphere. Although the MPL did not transmit telemetry data during this phase of operations, a JPL Special Review Board (SRB) determined the most probable cause of the MPL was premature shutdown of the descent engines due to the vulnerability of the software to transient signals.⁴⁰

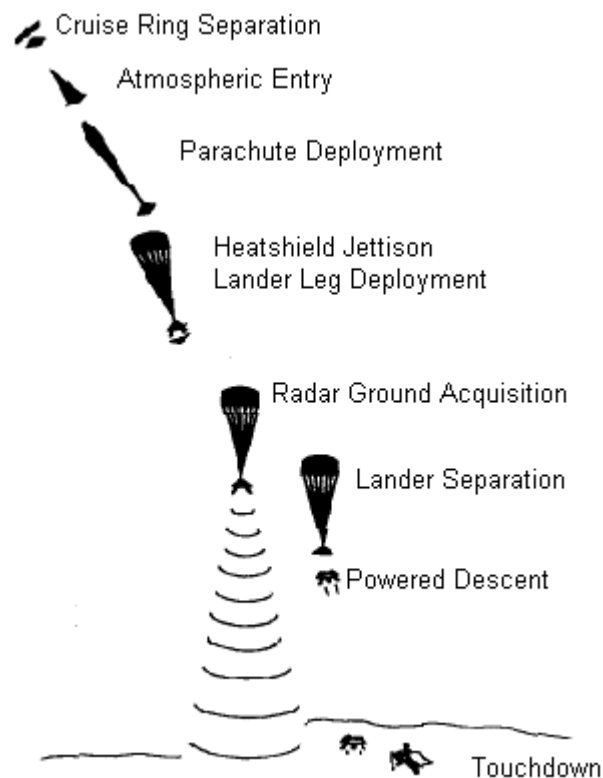


Figure 3.3.2.1.2-2 – MPL Landing Sequence

⁴⁰ Jet Propulsion Laboratory Special Review Board, "Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions," JPL-D-18709, March 22, 2000, p. xi.

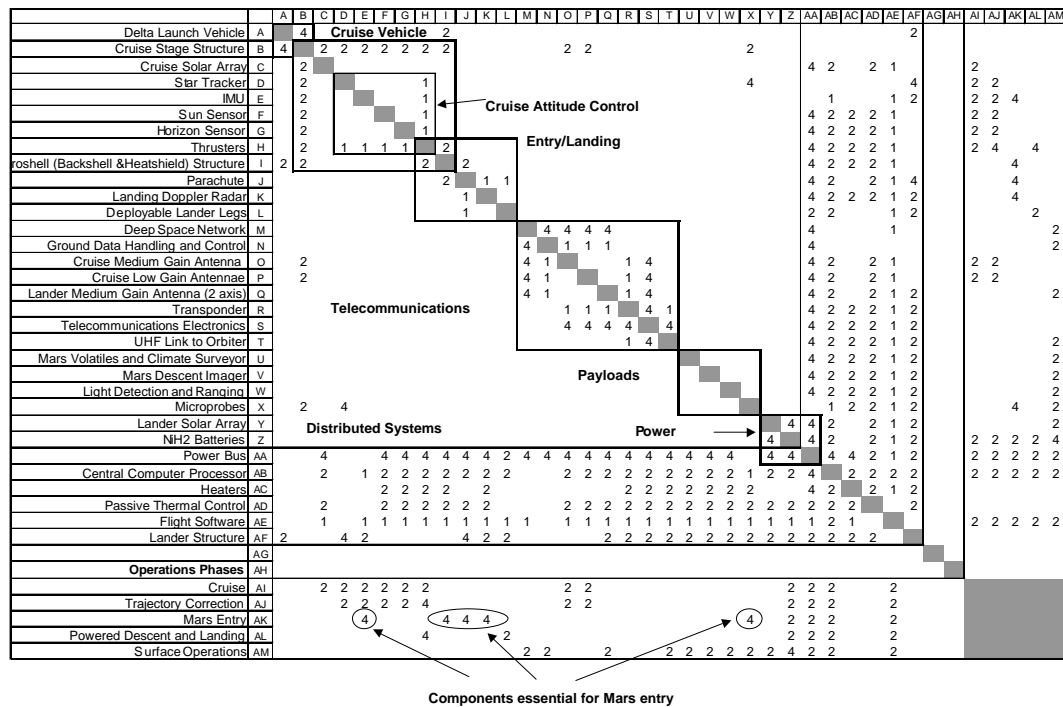


Figure 3.3.2.2.1-2 MPL Interface DSM

interfaces, software development and computer command and control.

The MPL interface DSM shows some distinctive clustering: the cruise vehicle, entry and landing systems, telecommunications, power and payload. The band of values near the bottom of the matrix shows the dependencies of the distributed systems interfaces are similar to the MCO's. The matrix also provides visibility into a major distinction of the MPL system architecture. A common propulsion system is used for trajectory maneuvers, attitude control, and powered descent. Thus, the thrusters can be seen as part of an overlap between the cruise propulsion functions and the elements of the remainder of the vehicle required for entry, descent, and landing.

Note that for both MCO and MPL an "invisible" cluster was drawn to identify the payload systems. These instruments have no direct interface amongst themselves except for a dependence in competing for the same system resources. The lack of inter-dependency supports an opportunity for independent development of each instrument.

The “Operational Phases” section of the MCO and MPL interface DSMs highlight the criticality of the components for each operational phase. This section of the DSM will be discussed more in the technology DSM; however the MPL interface DSM can be used to make a few simple observations. By examining the squares with values to the right of “Mars Entry” it can be seen there are multiple essential components (components with a value rating of 4). Basically, the matrix indicates that successful entry is going to rely heavily on the successful performance of the IMU, the aeroshell, parachute and landing radar. The microprobes also have a high criticality value during entry since this is the point where they separate from the main vehicle to make their journey to the surface. Several elements are seen to be critical for all phases of operations. As might be expected, components such as the power bus, computer processor, and software are required at a high level of criticality for all phases of operations. The battery is shown as essential for lander operations, since the batteries will fail and end landed operations when the Martian day becomes too short to allow the solar arrays to fully charge the battery.

3.3.2.2.2 MCO and MPL Technology DSM Analysis

The technology risk DSM provides some insight into the areas of risk concern for both of the Mars '98 missions. The MCO Technology Risk DSM can be found in Figure 3.3.2.2.2-1. The MCO used technology and methods similar to the MGS, thus most of the TRFs were low. However, two primary components with flight heritage were used in a different manner for the first time on MCO. The propulsion system used a different timing sequence for tank pressurization, and the processor was utilized as an all-in-one processor. The new application of this hardware for MCO is reflected with TRFs valued at 2. The TRF DSM shows that there are a few risk hot spots. For example, the matrix values indicate that development of the propulsion system could present moderate risk. The operations portion of the matrix shows that the performance of these components would be of highest concern during the trajectory correction and aerobraking operations. The high TRF rating on the central processor shows the impact of

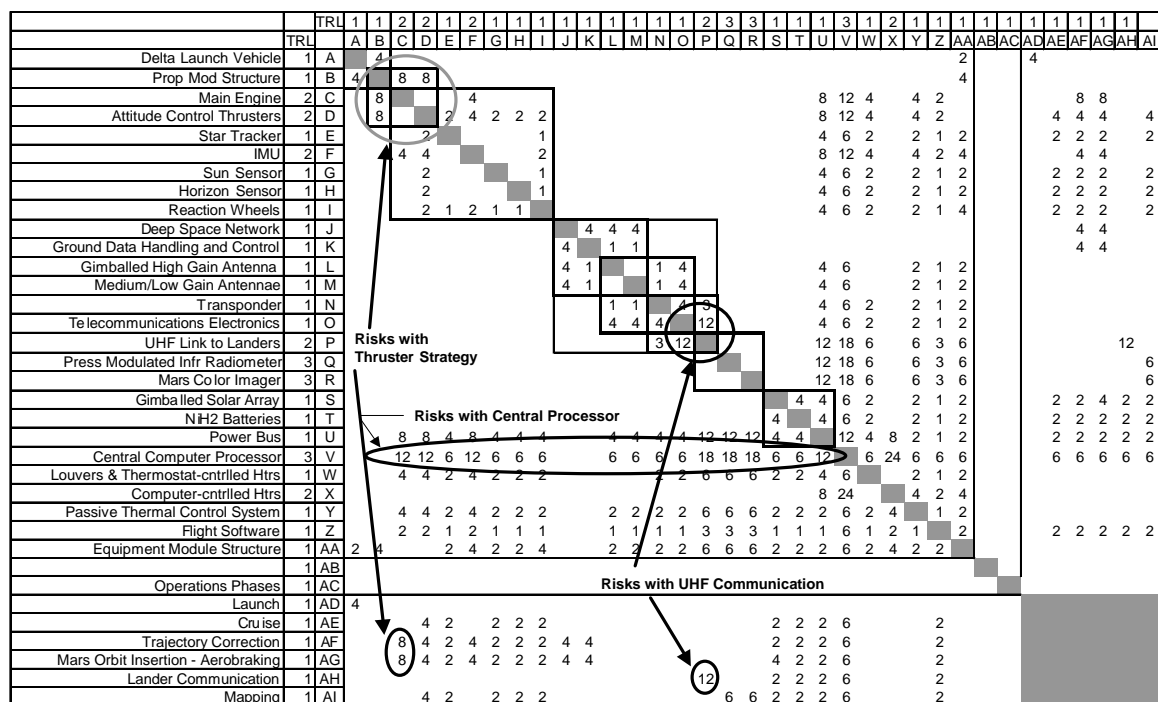


Figure 3.3.2.2.2-1 MCO Technology Risk DSM

UHF communication between the MCO and the MPL.

The MPL technology risk DSM can be found in Figure 3.3.2.2.2-2. The DSM shows the impact of the technical immaturity of the thrusters and UHF link in their respective functional subsystems. Interfaces with the central processor also exhibited higher risk values due to the moderate TRF assigned to it. The power bus also had some higher risk-rated interfaces, primarily due to the high TRFs of interfacing components. The higher values found in distributed system interfaces indicate potential for integration challenges with some of the less technically mature components. The operations section of the DSM highlights potential risk Mars Entry and Powered Descent phases. The high values indicate to some degree that the two operations are relying on less mature technology in these phases.

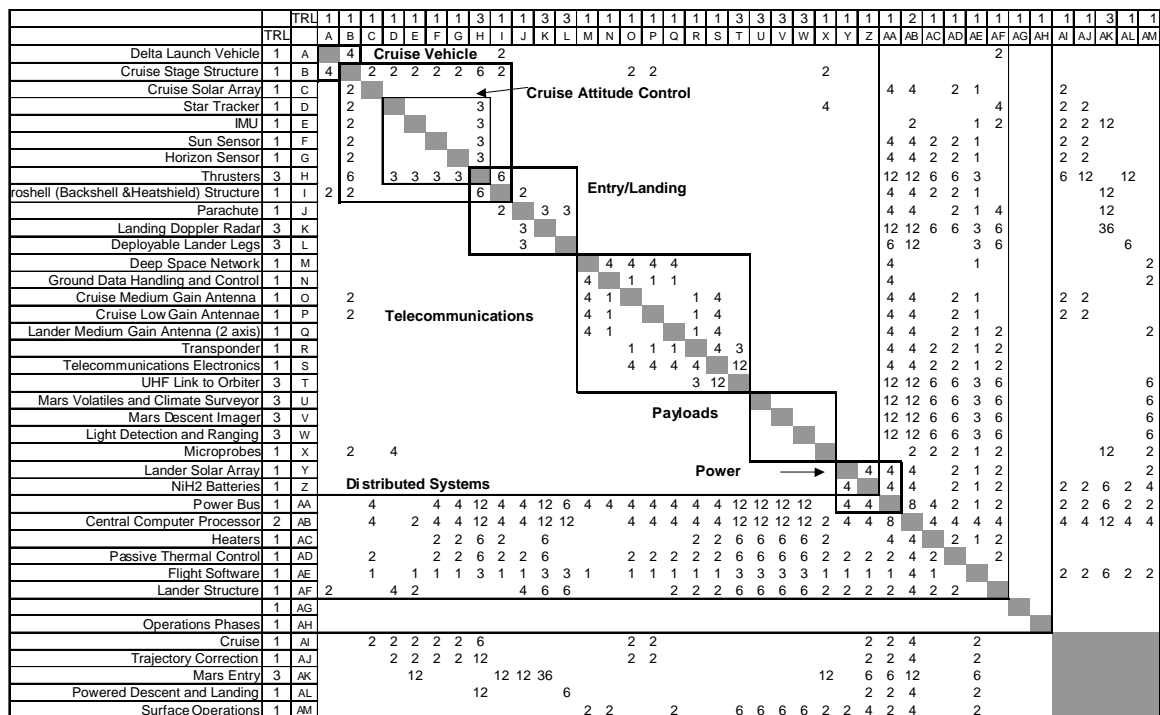


Figure 3.3.2.2.2-2 MPL Technology Risk DSM

3.3.2.3 Mars Surveyor '98 Lessons Learned Applicable to the DSM Analysis

3.3.2.3.1 MCO Lessons Learned Applicable to the DSM Analysis

The MCO MIB made twelve major observations related to the MCO Project's lack of a robust systems engineering team and the inadequacy of the systems processes.⁴¹ The observations made by the MIB are paraphrased below.

MCO MIB Observations

1. Absence of a mission systems engineer during operations phase.
2. Lack of definition of acceptable risk (in context of faster, better, cheaper philosophy).
3. Navigation requirements set at too high of a management level.
4. Significant system and subsystem design and development issues uncovered after launch.

⁴¹ Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," March 13, 2000, pp. 16-17.

5. Inadequate independent verification and validation of ground software.
6. Failure to complete the interface control process with rigor as well as verification of the ground system interfaces.
7. Absence of a fault tree analysis for mission operations.
8. Inadequate identification of mission-critical elements throughout the mission.
9. Inadequate attention, within the systems engineering process, to the transition from development to operations.
10. Inadequate criteria for mission contingency planning.
11. Insufficient autonomy and contingency planning to execute mission-critical operations scenarios.
12. A navigation strategy that was totally reliant on Earth-based, Deep Space Network (DSN) tracking of the MCO.

With the advantage of perfect hindsight, an assessment was made of both the interface and technology risk DSMs' ability to identify any indications of overall project risk areas. Five of the areas of the MIB's observations have potential for identification through DSM analysis. The DSM analysis was not anticipated to be able to provide any insight into the remainder of the observation areas.

Observation 1, absence of a mission systems engineer during operations phase –The MCO MIB report somewhat touches on the importance of good knowledge sharing between the development and operations phases. For example, the board noted:

“The operations navigation team was not intimately familiar with the attitude operations of the spacecraft, especially with regard to the attitude control system and related subsystem parameters. These functions and their ramifications for Mars Climate Orbiter navigation were fully understood by neither the operations navigation team nor the spacecraft team, due to inexperience and miscommunication.”⁴²

⁴² *ibid*, p. 18.

The Operations Phase section of the technology risk DSMs provides a specific view of the interaction between a component and the operations phase, namely how critical the component is to successful completion of a particular phase. However, it does not communicate the dependency for knowledge between the subsystem developer and the operator. Another DSM analysis could be developed to look specifically at the informational needs or availability of knowledge between the component developer and operator. This additional analysis could also provide information related to facilitating the transition between development and operations identified in Observation 9.

Observation 4 - Significant system and subsystem design and development issues uncovered after launch – Information was not available on which systems had design and development issues. It would be interesting forward work to look at whether the development issues were related to interfaces with a high technology risk rating.

Observation 5 - Inadequate independent verification and validation of ground software – With the benefit of hindsight, the DSN and Ground Data Handling and Control were given essential rating (“4”) in the trajectory correction maneuvers (TCMs) and Mars orbit insertion (MOI) operations. Thus, the technology risk matrix reflects a moderate risk level for these elements on those specific operations. In general, the technology risk DSM could be used to highlight an operational risk area. In this case, if the risk had been properly understood a priori, a mitigation strategy including ground validation might have been proposed.

Observation 8 - Inadequate identification of mission-critical elements throughout the mission – The main purpose of the Operations section of the technology risk DSM is to provide a means to visualize components critical to particular operational phases. The MCO technology risk DSM identifies concern with the proper function of many components during the TCM and MOI operations.

Observation 12 - A navigation strategy that was totally reliant on Earth-based, DSN tracking of the MCO – It is clear in hindsight that Earth-data was critical to the TCM and MOI maneuvers. With the DSN and ground systems identified as essential in the interface DSM, some risk level from this strategy

could be deduced from looking at the those components in the risk DSM and such a discovery in a future project analysis could be used to better manage risk.

3.3.2.3.2 MPL Lessons Learned Applicable to the DSM Analysis

In addition to establishing the probable cause of the failure of the MPL, the JPL Special Review Board (SRB) made findings and recommendations with respect to project implementation, project reviews, the design process, and verification and validation.

MPL Review Board Findings

1. Cost and schedule pressure impacted project staffing and key technical decisions.
2. Project reviews were held in a manner less rigorous than previous JPL projects and this streamlined approach was not documented in a review plan.
3. The systems engineering resources were insufficient to meet the needs of the project.
4. The verification and validation process had some deficiencies in addressing total system performance.

Of the four major findings outlined by the JPL SRB, three of these findings relate to early project implementation decisions. An assessment was made as to whether or not the analysis framework described in this thesis could provide any insight into these three finding areas.

Finding 1 - Cost and schedule pressure impacted project staffing and key technical decisions –

As described earlier, several articles have been written on the utilization of a component-based DSM, which can be utilized to identify categories of work teams that can be established to optimize information flow. The MPL interface DSM (Figure 3.3.2.2.1-2) shows that there are natural subsystem development

tasks as well as a large number of system integration tasks. Detailed project organization charts, particularly for the LMA project team, were not reviewed, however a few observations can be drawn based on the JPL SRB report. “In order to meet the challenges, the Laboratory decided to manage the project with a small JPL team and to rely heavily on LMA’s management and engineering structure.”

The DSM analysis cannot be used to assess an adequate level of staffing; however, it can be utilized as a means to identify key interface responsibilities which could then be used in the process of assigning specific responsibilities to work teams.

The JPL SRB report also describes the project team’s need to balance technology, cost, schedule and risk decisions. For example:

“The decision to use pulse-mode control for the descent engines avoided the cost and cost risk of developing and qualifying a throttle valve in exchange for a somewhat more difficult terminal descent guidance system algorithm... Although the risks in the mechanical and thruster were dealt with satisfactorily, the risks in the dynamics and control area were not completely retired and should have been more thoroughly addressed through analysis and test.”⁴³

The technology risk DSM provides an opportunity to look at the ramifications of these technical decisions. For example, this decision can be reflected in a TRF rating on the thruster and the matrix can provide a quick system overview of the impact of the decision. Each square or matrix area with a high-risk rating must somehow be adequately addressed in a risk mitigation strategy.

Finding 3 - The systems engineering resources were insufficient to meet the needs of the project –

The DSM analysis approaches described above can be used to identify a basic picture of the complexity of the interactions of the components in the project. A better understanding of the system complexity would enhance detailed planning would be required to identify resource requirements for any major project implementation area.

⁴³ JPL Special Review Board (2000), p. 7.

Finding 4 - The verification and validation process had some deficiencies in addressing total system performance – The JPL SRB felt the verification and validation (V&V) process had some deficiencies in the parachute, powered descent and touchdown phases for the MPL but, in general, the process was well planned and executed. The MPL project utilized a combination of similarity, analysis and test to validate the system and component performance. The SRB's primary observation was that simulation and other analyses were potentially compromised when tests used to develop or validate the system models did not have sufficient fidelity.

Chapter 4 Discussion of Results

This thesis presented a systems engineering analysis framework utilizing DSM to examine the structure of complex technical projects. Several planetary and earth observation spacecraft were used as case studies which were analyzed using two extensions of DSM analysis. This framework was intended to examine the project's architecture and technology decisions.

Chapter 2 provided an overview of DSM analysis and detailed the extension of previous works to generate an "interface DSM" and "technology risk" DSM. Chapter 3 provided a detailed analysis of each of the seven spacecraft case studies and identified findings from the two DSM analyses consistent with project lessons learned. This chapter is intended to summarize the analysis results and to critique the DSM analysis framework. The analysis summary viewed the case studies collectively to compare elements of the project's structure to characteristics of implementation consistent with project success or failure. The limitations of the proposed analysis framework were reviewed and suggestions for future work were provided.

4.1 Summary of the Interface and Technology Risk DSM Case Study Analysis

The DSM analysis was performed on each of the seven spacecraft case studies. The analytical process used for the case studies consisted of four basic steps (described in Section 2.2.3):

1. Identify and quantify interface dependence between components;
2. Reorder components to identify subsystem clusters and distributed systems in the DSM;
3. Identify operational phases and identify component criticalities to each phase;
4. Assign TRFs to each component and generate technology risk DSM.

The interface and technology risk DSMs were examined to identify patterns, clusters, and high technology risk values. The combination of the two DSMs provided insight into the overall project

structure. Following a review of lessons learned described by project team members, an attempt was made to relate the DSM discoveries to project implementation lessons.

4.1.1 System Architecture, Project Organization and Development Strategy

Ulrich and Eppinger (2000) have identified two extreme types of product architecture: modular and integral.⁴⁴ The two concepts are summarized below.

Modular architecture has two properties:	Integral architecture has one or more of the following:
<ul style="list-style-type: none"> • Major building blocks implement one or few functional elements in their entirety • Interactions between major building blocks are well defined and are generally fundamental to the primary functions of the product 	<ul style="list-style-type: none"> • Functional elements are implemented using more than one major building block • A single building block implements many functional elements • Interactions are ill-defined and may be incidental to primary functions

Once clustered, the interface DSMs for the seven cases were studied to identify a general sense of the project's architecture. In the component sections of the interface DSMs presented in Chapter 3, general patterns gave a view of the degree of subsystem interdependence in the architecture. A scale was drawn representing system architectures ranging from modular to integral and the seven case studies were mapped on to this scale in Figure 4.1-1. On the left side of the scale, interface DSMs with no overlapping subsystems and a small number of distributed systems would be considered more modular or independent. SAMPEX provided a good example of this pattern. DSMs exhibiting a pattern with subsystems that overlap and/or have a large number of distributed systems were classified as integral. The Mars Pathfinder case showed the highest degree of integrality from the cases studied.

Pimmler and Eppinger (1994), McCord and Eppinger (1993), Eppinger (1997), and Browning (1997) have utilized component DSM to identify optimized organizational team structures to facilitate the transfer of information between the subsystem development teams. The interface DSM development

⁴⁴ Ulrich and Eppinger (2000), pp. 183-184.

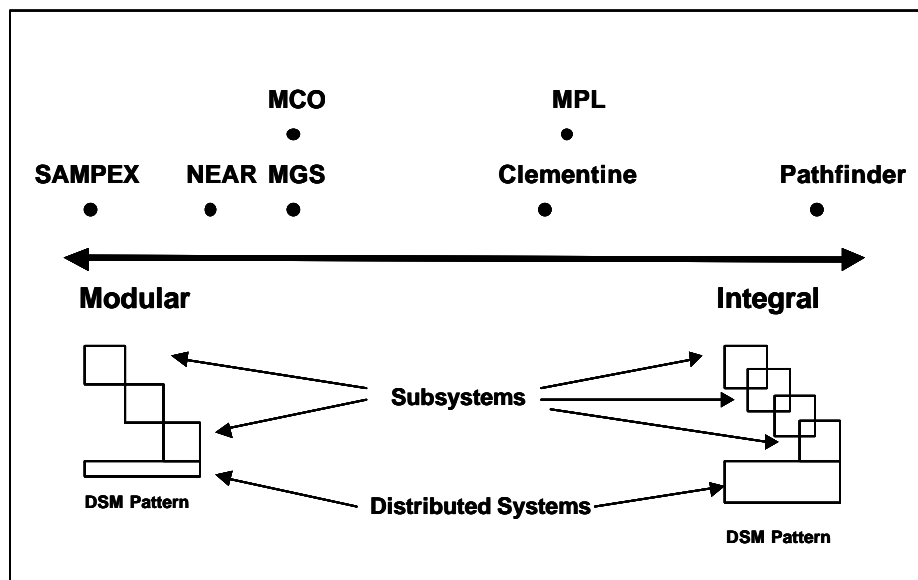


Figure 4.1.1-1 Mapping of System Architecture for the Cases Studied

encompasses the process identified by these earlier works and extends it to consider the mission operations.

The case studies provide good contrast for comparing the alignment of the system architecture and organizational structure. Take, for example, the NEAR and Mars Pathfinder projects which were both part of NASA's Discovery Program. Both NEAR and Pathfinder developed spacecraft for launch within three years, however these organizational approaches differed vastly. NEAR was staffed primarily from JHU's matrix organization while Pathfinder utilized a dedicated, project team with many of the key team members co-located. Both strategies worked well for the basic structure of the respective projects. In the NEAR case, the interface DSM analysis tool (Figure 3.2.2.2-1) demonstrated an ability to clearly identify the subsystem independence, which was well aligned with the utilization of a matrix organization. In contrast, the Mars Pathfinder interface DSM (Figure 3.2.1.2-2) showed a large number of interdependent subsystems and a co-location strategy provided for rapid flow of information to support integration. NEAR and Pathfinder also utilized a different operations strategy. Pathfinder took eight months to get to Mars and operated on the surface for almost 90 days while NEAR took four years to get to the asteroid Eros and studied the asteroid for more than a year. Pathfinder utilized many of the

subsystem developers as spacecraft operators and the duration of the mission enabled this approach. NEAR used a dedicated operations team in a mission operations center at JHU.

The SAMPEX interface DSM in Figure 3.1.1.2-1 indicates a pattern consistent with a highly modular architecture. With this architecture, the project team utilized a mix of dedicated project personnel and several integration functions were supported by the matrix organization. Some of these integration functions supported several of the SMEX missions. The organizational structure worked well for the individual project as well as for providing an infrastructure to capture knowledge that would be beneficial for future SMEX missions. SAMPEX was operated out of the Project Operations Control Center at GSFC. The spacecraft was designed for a low level of operational interaction. The science collection was fairly autonomous and was recorded on-board for transmission to Earth twice daily.

The three Mars Surveyor missions had similar system architectures and organizational implementation approaches. The three missions were led by NASA JPL with Lockheed Martin Astronautics as the prime contractor for spacecraft development. Spacecraft operations for the three missions were conducted by the Mars Surveyor Operations Project (MSOP). MGS successfully accomplished its goals and is still in operation today. MCO and MPL were both lost as they approached Mars. The interface DSMs for the three projects (Figures 3.3.1.2-1, 3.3.2.2.1-1 and 3.3.2.2.1-2 respectively) show fairly independent subsystems, with similar functions requiring systems integration. The operations section of each of the interface DSMs highlights components that were critical for mission operations. In the cases of MGS and MCO, propulsion components were essential to trajectory correction to enter into Martian orbit. For MPL, the EDL components were essential for the entry and landing phase.

Since MGS was successful and the MCO and MPL failed, the interface DSM analysis by itself does not indicate a difference in the spacecraft or organizational architecture that indicates a fundamental flaw in the structure of separate development and operations organizations. However, in its investigation of the MCO failure, the MIB noted that there were inadequate communications between project elements and there was an inadequate systems engineering transition process from development to operations.

Further understanding of the MCO project organization structure would be of interest to determine if the communication problem was exacerbated by a mismatch between the organization and architecture of the subsystems and the distributed systems.

The MCO MIB noted another contributing cause to the failure was that the operations navigation team was not intimately familiar with the spacecraft characteristics. None of the DSM analyses presented could provide an indication of this potential problem; however development of a DSM that includes an indication of an operational phase's dependency for knowledge about spacecraft characteristics would be of benefit in providing an indication of the transition from development to operations. For example, an analysis indicating an operator's dependence on spacecraft component knowledge would show great contrast between autonomous science operations on SAMPEX and the high degree of planning and interaction involved with trajectory correction in interplanetary travel.

The case analyses also showed some relationship between project success and alignment between architecture and development strategy. Both NEAR and SAMPEX utilized a strategy to develop subsystems in parallel. The highly independent subsystems in the interface DSMs for SAMPEX and NEAR appear to support this strategy. In fact, the NEAR project took a mass penalty in the spacecraft by establishing and maintaining a clean interface between the propulsion module and the rest of the spacecraft. The concurrent engineering and parallel development of components was successful in these projects which was consistent the modular nature of their respective spacecraft architectures.

The Clementine interface DSM shows a combination of independent subsystems and a large number of distributed systems that were required for integration. Clementine also had a short development schedule – Clementine was launched after a 22-month development phase. The project was staffed by a small “hand-picked” team and all design, development, testing and integration was conducted in a single facility. The interface DSM might indicate that concurrent development could occur in a more dispersed fashion than actually took place. However, an argument could be made that the patterns of the interface DSM were consistent with the management approach since components with flight heritage were concurrently developed by experienced vendors. A counter argument could be made that the co-

located team was not consistent with the architecture. The mission was schedule-driven and the co-located team was essential to speed up information flow. In this case, looking at the interface DSM, the system architecture and the organization was not enough. The schedule pressure drove the project implementation strategy, and this information could indicate that conclusions drawn from the DSM analysis framework may not apply in projects that are excessively constrained in schedule, technology challenges or cost.

4.1.2 Risk Management

The NASA Systems Engineering handbook notes that “Risk management comprises purposeful thought to the sources, magnitude, and mitigation of risk, and actions directed toward its balanced reduction.” The handbook identifies four elements in a risk management strategy: risk planning, risk identification and characterization, risk analysis and risk mitigation and tracking. (See Figure 4.1.2-1)⁴⁵ The handbook also identifies 13 techniques to aid in risk management – five of these techniques were identified to identify and characterize risk. These techniques included expert interviews, independent assessment, risk templates, previous project lessons learned and tools such as fault trees. Mars Pathfinder successfully managed risk in their project by identifying risks through techniques like expert interviews, and then allocating schedule and cost resources to reduce risk.

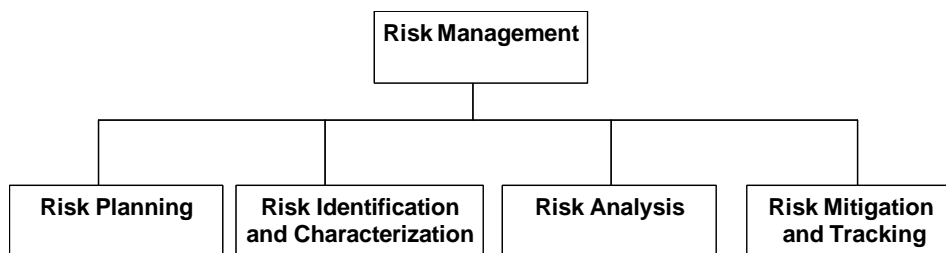


Figure 4.1.2-1 NASA Risk Management Overview

⁴⁵ National Aeronautics and Space Administration, “NASA Systems Engineering Handbook,” SP-6105, June 1995, p. 38.

The technology risk DSM is another tool that can be used as a tool to help identify and characterize risk. The technology risk matrix identifies potential subsystem risks by factoring in the dependency of two elements at their interface. By developing this matrix, high values can indicate risky “hot spots.” Particular attention should be paid to clusters of high values indicating a risky subsystem. The technology risk DSM also provides a relative indication of a component’s severity of consequences in completing a critical operation. Components that are essential to an operation and have some development risk are going to reflect a high value in the operations section of the technology risk DSM. Figure 4.1.2-2 below shows some of the highest technology risk values from the component and operations sections of the Mars Pathfinder technology risk DSM.

The interface DSM included an approach to examine the impact of component criticality on each of the major operational phases of the project. The technology risk DSM provided a view of the impact of the inherent technology risk of a component on the overall system. Examining patterns in these two DSMs could be used to expand the system view of project planners and enhance project implementation planning.

		TRL	1	1	1	4	3	3	3	2
		TRL	A	B	C	D	E	F	G	H
Delta II Launch Vehicle	1	A		4		8				
Cruise Stage Structure	1	B	4		2	8				
Cruise Power System	1	C		2						
Aeroshell (Heatshield & Backplane)	4	D	8	8			24			32
Parachute	3	E				24		36		24
Solid Rocket Assisted Decelerator	3	F					36			24
Airbags	3	G								24
Backshell Pyro Switching & Pyros	2	H				32	24	24	24	

Operations Phases	1	AS								
Cruise	1	AT				2				
Trajectory Correction	1	AU				2				
Entry, Descent & Landing	1	AV					16	12	12	12
Surface Deployment	1	AW								

Figure 4.1.2-2 Detailed Views of the Mars Pathfinder Technology Risk DSM

4.2 Observations from the DSM Case Study Analyses

The goal of this thesis was to develop an analytical framework that could be utilized to provide a more holistic view of a project from the conceptual development through its operational mission. The case study analyses provided an opportunity to reflect on the capabilities of the DSM analysis tool.

- Good decision-making requires in-depth technical understanding and knowledge of programmatic resources and design margins at all levels. The two DSMs can provide a guide to identifying key areas where there must be a thorough technical understanding must exist.
- The proposed analytical framework should be viewed as a tool to facilitate discussions between project planners and expand viewpoints with respect to project implementation which could affect all aspects of the project life cycle. The level of detail used to generate the DSMs can vary, thus future use of this tool should be tailored as needed to maximize the view of the system and project life.
- A key element to project success is aligning mission objectives, project architecture, technology and implementation approaches. Both NEAR and Pathfinder demonstrated successful completion of highly complex technical achievements within a very short development time, but the goals were achieved with vastly different methods. NEAR used mature hardware and a matrix organization while Pathfinder demonstrated lots of new technological approaches and a co-located project team. Both strategies worked well for the basic structure of the respective projects.
- The technology risk DSM could be a valuable tool for identifying potential “hot spots” where a thorough risk mitigation strategy will be required. The technology risk DSM highlighted many subsystem development areas with high risk that matched well with those identified by and addressed by the project teams.
- The technology risk DSMs were written based on the technology readiness at the time of launch after the verification and test programs were complete. A technology risk DSM generated at the concept review based on component maturity level would likely be a better indicator of the potential unplanned rework.

- Similarly, during early planning, TRFs could be used to determine the adequacy of a V&V program. For example, a priori assignment of TRFs, assuming TRF levels following a completely successful verification program could be used to show the “best case” of mitigated risk. Figure 4.2-1 shows an example of how the EDL portion of the technology risk matrix could have been viewed at concept selection and following the verification program. At the time of the technology selection, the TRFs were actually higher than they were before launch. The extremely high technology risk values in this area could be used to identify an area where unpredicted activities would be required and certainly could be used to justify budget and schedule reserves. An assessment could also be made as to whether or not the V&V program provides an acceptable level of risk mitigation.

At Concept Selection											
	TRF		1	1	1	4	4	5	2	1	
	TRF	A	B	C	D	E	F	G	H	I	
Delta II Launch Vehicle	1	A		4	8						
Cruise Stage Structure	1	B	4		2	8					
Cruise Power System	1	C		2							
Aeroshell (Heatshield & Backplane)	4	D	8	8			32			32	
Parachute	4	E				32		64		32	
Solid Rocket Assisted Decelerator	4	F					64			32	
Airbags	5	G								40	
Backshell Pyro Switching & Pyros	2	H				32	32	32	40		8
Lander Shunt Limiter Unit	1	I								8	

Before Launch											
	TRF		1	1	1	4	3	3	3	2	1
	TRF	A	B	C	D	E	F	G	H	I	
Delta II Launch Vehicle	1	A		4	8						
Cruise Stage Structure	1	B	4		2	8					
Cruise Power System	1	C		2							
Aeroshell (Heatshield & Backplane)	4	D	8	8					24		32
Parachute	3	E							24	36	24
Solid Rocket Assisted Decelerator	3	F							36		24
Airbags	3	G									24
Backshell Pyro Switching & Pyros	2	H							32	24	24
Lander Shunt Limiter Unit	1	I									8

Figure 4.2-1 EDL Subsystem Technology Risk Matrix at Concept Selection and at Launch

4.3 Future Extensions of Interface and Technology Risk DSM Analysis

The summary of the case studies has pointed out some of the strengths and weaknesses of the interface and technology risk DSM analyses. Some suggestions for future work extending the interface and technology risk DSM analyses are offered to enhance future analytical capabilities.

- The input into some areas of the matrices has some level of subjectiveness. However, utilizing spreadsheets to develop the DSMs provides an opportunity to perform some level of sensitivity

analysis. Different values for interface dependency or for a component's TRF could quickly be tested and the impact of the changes could be studied to determine their relative importance.

- The DSM analysis performed does not adequately characterize the interdependence of knowledge between the hardware development team and the operations phase. In the Pathfinder project, the developers became spacecraft operators and their in-depth knowledge of their subsystems was a key to the pathfinder success. In contrast, the MCO was lost in part because of the separation of the development and operations team and the lack of information shared between the two. Future work could provide insight into this area by developing a third DSM, which would identify the degree of component knowledge required by an operator in each phase of operations.
- The current form of the proposed DSM analysis does not provide an indication of the intensity of operational interactivity with the spacecraft. Future work should include a means to have some indication as to how architectural and technology decisions could extend or reduce real-time operations.
- Observations made from the DSM analysis framework may not apply in projects that are excessively constrained in schedule, technology challenges or cost. The proposed analysis should be extended to other cases to better define the capability of the analysis framework.

Chapter 5 Summary and Conclusions

The motivation for this thesis was to examine why some of NASA's projects of the 1990's had a high correlation of failure associated with a few common themes – inadequate project reviews, poor risk management, insufficient testing, and inadequate communications. A systems engineering analysis framework, utilizing DSM analysis, was presented as tool for planners to develop and evaluate project implementation approaches to minimize the potential for failure related to these common themes.

The DSM analysis was used as part of a general systems engineering review of seven spacecraft projects. The analysis framework was successful at providing a representation of many of the issues and insights identified in the literature by team members from the respective projects.

Two different approaches of DSM analysis were utilized. The interface DSM mapped the dependence of components on one another, which was measured based on a rating of the strength of the interface between the two components. Major operational phases were also included in the DSM to provide an opportunity to view the impact of component criticality on the respective operational phases. The technology risk DSM included a TRF, which showed increasing value for increasing technological risk. The matrix was then used to identify the patterns of system level risk based on the selection of components with varying TRFs.

The analysis of the spacecraft cases helped to identify two fundamental elements that are essential for a project to be successful:

1. Implementation planning must consider a project from the view of the entire mission life cycle.

In complex technical projects, such as NASA's spacecraft missions, consideration must be given to the mission as whole. The strategy managers use to execute a project must balance the needs and resources across all phases of the project life, and insure seamless transitions through all phases from development to operations.

2. For a complex technical project to be successful, it is essential that alignment exists between system architecture, organization, development and operations strategies.

There is no single approach for mission success. The NEAR spacecraft and Mars Pathfinder both achieved mission success, however the implementation approaches were vastly different. The key to success of both projects was the alignment of their implementation strategies. Mars Pathfinder wanted to demonstrate new technologies for interplanetary travel. The severe mass constraints for a Mars mission led to a highly integral design. Their dedicated project team was collocated to facilitate efficient information flow between development teams. The uncertainty of new technology led to a plan for an extended test and verification process. The NEAR project team used mature technology in the first spacecraft to visit an asteroid. Schedule focus led to a philosophy of concurrent development of subsystems. The team focused on establishing clean interfaces at expense of launch mass to mitigate issues associated with integration. The key to the success of both of these projects was that their strategies were aligned.

Successful project implementation requires an understanding of the project structure, knowing the potential challenges that lie ahead, and developing and managing a strategy to manage those risks. The case study analyses demonstrated that the DSM analysis framework could be used to develop a deeper understanding of the underlying system architecture and the risks associated with selection of technology.

Understanding the architecture of the system and providing a means to identify interfaces with a high degree of interdependence can provide an indication of where a high degree of information flow will be required. The knowledge of this relationship will be important to organizing the project team to develop and operate a complex system. Similarly, identifying and characterizing risks inherent in a mission, particularly those affected by technology decisions is an essential element of risk management. The DSM analysis framework presented provides a method to identify the basic elements of a project structure and provides a means for a project planning team to go through a discovery process for examining feasible architecture alternatives, understanding the potential system impacts of basic decisions, and identifying potential risk areas.

Bibliography

- Baker, D. N., Mason, G. M., Figueroa, O., Colon, G., Watzin, J. G., and Aleman, R. M., "An Overview of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) Mission," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 31, No. 3, May 1993.
- Bearden, David A., "A Complexity-Based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?" *Fourth IAA International Conference on Low-Cost Planetary Missions*, JHU/APL, Laurel, MD May2-5, 2000.
- Blanchard, Benjamin S. and Fabrycky, Walter J., *Systems Engineering and Analysis – Third Edition*, Upper Saddle River, NJ: Prentice Hall, 1998.
- Browning, Tyson R., "Multi-Team Integration: Interdependence and Integrative Mechanisms," *Proceedings of the Sixth Annual International Symposium of INCOSE*, Boston, July 7-11, 1996, pp. 787-794.
- Browning, Tyson R., "Mechanisms for Interteam Integration: Findings from Five Case Studies," *Proceedings of the Seventh Annual International Symposium of INCOSE*, Los Angeles, Aug.3-7, 1997, pp. 649-656.
- Browning, Tyson R., "Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development," PhD Dissertation, Massachusetts Institute of Technology, December 1998. (1998a)
- Browning, Tyson R., "Use of Dependency Structure Matrices for Product Development Cycle Time Reduction," *Proceedings of the Fifth ISPE International Conference on Concurrent Engineering: Research and Applications*, Tokyo, Japan, July 15-17, 1998. (1998b)
- Browning, Tyson R., "Process Modeling with Design Structure Matrices (DSMs)," *INCOSE Insight*, Vol. 2, No. 3, pp. 15-17, 1999.
- Carr, P. D. et al., "NEAR Cruise and Mathilde Flyby Mission Operations – Report from the Front Lines of Low Cost Missions," *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 465-473, 1999.
- Clark, Kevin P., "Mars Global Surveyor Mission Assurance: Key Approaches for Faster, Better, Cheaper Missions," *1998 IEEE Aerospace Conference*, 1998 IEEE , Volume: 5 , 1998 Page(s): 491-506.
- Committee on Planetary and Lunar Exploration (COMPLEX) Space Studies Board Commission on Physical Sciences, Mathematics, and Applications, National Research Council, "Lessons Learned from the Clementine Mission," 1997.
- Cook, Richard, "Mars Pathfinder Mission Operations Concept," *Acta Astronautica*, Vol. 39, Nos. 1-4, pp. 71-80, 1996.
- Coughlin, Thomas B., "NEAR: The First Launch in the Discovery Program," *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 227-233, 1999.
- Dallas, S. Sam, "Mars Global Surveyor Mission," *1997 IEEE Aerospace Conference, Snowmass at Aspen, CO, Feb. 1-8, 1997*, pp. 173-179 of Proceedings.

- Eppinger, Steven D., Whitney, Daniel E., Smith Robert P., and Gebala, David A., "A Model-Based Method for Organizing Tasks in Product Development," *Research in Engineering Design* 6: 1-13, 1994.
- Eppinger, Steven D., "A Planning Method for Integration of Large-Scale Engineering Systems," *International Conference on Engineering Design, ICED 97 Tampere*, August 19-21, 1997.
- Eppinger, Steven D., and Salminen, "Patterns of Product Development Interactions," *International Conference on Engineering Design, ICED 01 Glasgow*, August 21-23, 2001.
- Figuerola, Orlando and Colón, Gilberto, "SAMPEX," in *Reducing Space Mission Cost*, edited by Wertz, James R. and Larson, Wiley J., Space Technology Library, Microcosm Press, Torrance, CA, 1996, pp. 397-409.
- Horan, Donald M. and Berkowitz, Bruce D., "Clementine," in *Reducing Space Mission Cost*, edited by Wertz, James R. and Larson, Wiley J., Space Technology Library, Microcosm Press, Torrance, CA, 1996, pp. 427-447.
- Huntress, Wesley T. Jr., "The Discovery Program," *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 207-213, 1999.
- International Council on Systems Engineering, *Systems Engineering Handbook*, Release 1.0, January 1998.
- Jet Propulsion Laboratory, "Mars Global Surveyor Risk Management Plan," JPL D-12089, September 30, 1994.
- Jet Propulsion Laboratory, "Mars Surveyor '98 Project Mission Plan and Databook," JPL-D-13652, August 8, 1997.
- Johns Hopkins University Applied Physics Laboratory, "Near Earth Asteroid Rendezvous – A Guide to the Mission, the Spacecraft, and the People," <http://near.jhuapl.edu>, December 1999.
- Kleiner, Brian M. and Newcomb, John F., "NEAR, Rendezvous with Faster, Better, Cheaper NASA Projects," Case Study written for NASA Academy of Program and Project Leadership, <http://appl.nasa.gov>, 1997.
- Mars Climate Orbiter Mishap Investigation Board, "Mars Climate Orbiter Mishap Investigation Board Phase I Report," November 10, 1999.
- Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," March 13, 2000.
- McCord, Kent. R. and Eppinger, Steven D., "Managing the Integration Problem in Concurrent Engineering," Massachusetts Institute of Technology Sloan School of Management Working Paper 3594-93-MSA, August 1993.
- Muirhead, Brian K., "Mars Pathfinder Flight System Design and Implementation," *1996 IEEE Aerospace Applications Conference Proceedings*, Vol. 2, pp. 159 -171, 1996.

- Muirhead, B.K., "Mars Pathfinder Flight System Integration and Test," *1997 IEEE Aerospace Conference Proceedings*, vol. 4, pp. 191 -205, 1997.
- Muirhead, Brian, and Pritchett, Price; *The Mars Pathfinder Approach to Faster-Better-Cheaper*, Pritchett & Associates, Inc. 1998.
- National Aeronautics and Space Administration, "1998 Mars Missions Press Kit," December 1998.
- National Aeronautics and Space Administration, "NASA Systems Engineering Handbook," SP-6105, June 1995.
- Palluconi, Frank D. and Albee, Arden, L., "Mars Global Surveyor: Ready for Launch in November 1996," *Acta Astronautica*, Vol. 40, Nos. 2-8, pp. 511-516, 1997.
- Pimmler, Thomas U. and Eppinger, Steven D., "Integration Analysis of Product Decompositions," *DE-Vol. 68, Design Theory and Methodology – DTM '94*, ASME 1994.
- Regeon, P. A., Chapman, R. J., Baugh, R., "Clementine, 'The Deep Space Program Science Experiment,'" *Acta Astronautica* Vol. 35, Suppl., pp307-321, 1995.
- Santo, A. G., Lee, S. C., and Gold, R. E., "NEAR Spacecraft and Instrumentation," Undated document from <http://near.jhuapl.edu>.
- Santo, Andrew G., Lee, Susan C., and Cheng, Andrew F., "Near Earth Asteroid Rendezvous Spacecraft Overview," *Proceedings of the 1996 Aerospace Applications Conference*, Vol. 2, pp. 131-141, 1996.
- Sarsfield, Liam, "Cosmos on a Shoestring – Small Spacecraft for Space and Earth Science," Rand Study for the Office of Science and technology Policy (OSTP) and the Office of Management and Budget, 1998.
- Senge, Peter, *The Fifth Discipline: the Art and Practice of the Learning Organization*, New York: Doubleday, 1990.
- Sidney, Wayne and Lee, Wayne, "Mars Global Surveyor Mission Plan," (draft) JPL MGS Document 542-405, June 30, 1995.
- Spear, Anthony J., "Mars Pathfinder's Lessons Learned from the Mars Pathfinder Project Manager's Perspective and the Future Road," *Acta Astronautica*, Vol. 45, Nos. 4-9, pp. 235-247, 1999.
- Ulrich, Karl T. and Eppinger, Steven D., *Product Design and Development*, McGraw Hill, 2000.
- Wertz, James R. and Larson, Wiley J., *Reducing Space Mission Cost*, Space Technology Library, Microcosm Press, Torrance, CA, 1996.
- Wiley, S., Herbert G. and Mosher, L., "Design and Development of the NEAR Propulsion System," *AIAA 95-2977, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, San Diego, CA, July 10-12, 1996.

Website References:

Mars Global Surveyor: <http://mars.jpl.nasa.gov/mgs>

Mars Polar Lander: <http://mars.jpl.nasa.gov/msp98/lander/>

Mars Climate Orbiter: <http://mars.jpl.nasa.gov/msp98/orbiter/>

Mars Surveyor: <http://nssdc.gsfc.nasa.gov/planetary/marsurv.html>

Design Structure Matrix: <http://web.mit.edu/dsm>

Appendix – Case Study Analysis Assumptions

The following assumptions were made during the generation of the interface and technology risk DSMs.

Case 1: SAMPEX DSM Assumptions

- Physical interfaces were assumed according to the spacecraft architecture diagram in Figueroa and Colón (1996).
- Power distribution energy interfaces were assumed based on electrical layout in Baker (1993).
- New innovations in the project include 1773 data bus, Processors (CTT, RPP and DPU); these components were assumed to be at TRF value of 3. (Based on Baker (1993) “there are many innovations including powerful onboard processors, optical fiber busses, solid state memory units, and a highly integrated mechanical design.”)

Case 2: Clementine DSM Assumptions

- Architecture assumed to follow detailed block diagram in Regeon (Figure 4).
- Structure: Launch vehicle adapter interfaces with Titan and Interstage adapter; interstage adapter goes between main SC structure and LV adapter; these are physical and energy interfaces
- Sensors go primarily to sensor processor but there is an indirect information interface to the thrusters etc.
- Assume all electronics boxes have heater control
- All electronics boxes have major interface with flight software
- All sensors and effectors have major interface with flight software
- Based on COMPLEX Lessons Learned the following components were assumed to have higher TRF's
 - Sensor computer – 2
 - Release mechanism – 3
 - Battery – 3
 - IMU – 3
 - Star tracker – 2
 - UV/Vis imager & High res Imager – 2
 - Laser Transmitter, Near Infrared Imager, Long wave Imager – 3

Case 3: Mars Pathfinder DSM Assumptions:

- System architecture information was taken from system block diagram found in Muirhead (1996)
- There are three major spacecraft structures: cruise stage, entry vehicle, and lander.
- Launch vehicle gives energy to the 3 major structural elements – an energy transfer.
- The cruise stage acts as a physical interface to the launch vehicle
- All active components have a physical and an energy interface to power via the power distribution unit.
- Components powered during cruise get primary thermal control through active Freon fluid loop (e.g. battery and electronics).
- All powered components must release some of their energy through passive thermal control.
- All thrusters have a physical interface with and transfer energy to the cruise structure.
- Data and command information transfer assumed via the Muirhead system block diagram.
- Major attitude information components are located on the cruise stage.
- Thrusters have physical and energy interface to cruise structure.
- Deep Space Network gets energy and information from the spacecraft antennae.
- Software had indirect information exchange with sensors and effectors but direct information interface to the flight computers.
- Parachute interfaces with the aeroshell's backshell and has a major structural (energy) interface.
- Parachute interfaces with the lander structure and has a major structural (energy) interface.
- The block diagram of Muirhead (1996) was simplified. The block diagram simplification assumptions include:
 - Cruise Power System consists of cruise solar arrays, cruise shunt limiter, and cruise shunt radiators
 - Power Distribution and Control consists of the primary power control unit and power distribution unit.
 - Lander shunt radiators are considered part of the passive TCS
 - The Telecommunications Boards - VME consist of: a) Reed Solomon Downlink Board, b) Hardware command decoder
 - The Telecommunications Boards - TEL consist of: a) telemetry modulation units, b) command detector units
- Assume the science instruments are essential for their operational use (even though one instrument loss could still permit some degraded operations).

Case 4: NEAR DSM Assumptions

- Launch vehicle gives energy to propulsion and spacecraft structure – an energy transfer
- Spacecraft structure consists of spacecraft adapter (main forging) two decks, and 8 side panels; It has a physical interface to propulsion structure and other physical components
- Propulsion structure interfaces to propulsion components
- Thrusters have physical and energy interface to propulsion structure
- Helium tanks pressurize other tanks so a physical and energy interface is assumed
- The power bus has a physical and energy transfer to major system components
- The power switching relays are not distinguished from the power bus
- Power conditioning supports the elements to regulate the power system elements only
- Power switching units are assumed to interface with major command effectors (e.g. thrusters) and on/off for major systems
- Attitude control components have physical and information interface to the attitude interface unit (AIU)
- Deep Space Network gets energy and information from the spacecraft antennae
- All powered components must transfer energy via passive thermal control
- All powered components had thermostatically controlled heaters
- Assumed all components had high technology readiness
- The LVA thrusters are used during transit, rendezvous and science operations will use the monopropellant thrusters.

Case 5: Mars Global Surveyor:

- Spacecraft's center module consists of two smaller modules: the equipment module, which contains the spacecraft's electronics and scientific equipment, and the propulsion module which holds the tanks and rocket engines.
- Spacecraft structure consisted of four sub-assemblies known as the equipment module, the propulsion module, the solar array support structure, and the high gain antenna support structure.
- The equipment module's main function involves housing the avionics packages and science instruments.
- With the exception of the Magnetometer, all of the science instruments were bolted to the nadir equipment deck, mounted above the equipment module
- The propulsion module serves as the adapter between the launch vehicle and contains the propellant tanks, main engines, and attitude control thrusters.
- Two solar arrays mount close to the top of the propulsion near the interface between the propulsion and equipment modules.
- Rectangular shaped, metal drag "flaps" increase the total surface area of the array structure to increase the spacecraft's ballistic coefficient during aerobraking.
- The two Magnetometer sensors were mounted on the end of each solar array, in between the array and the flap.
- In addition to the solar arrays, the high gain antenna deploys from propulsion module.
- Command & Data Handling
 - has 6 major subcomponents:
 - Flight computers or standard control processors SCPs
 - Controls Interface Unit – connects to other s/c components
 - Engineering data formatter
 - Payload data subsystem
 - Cross-Strap Unit
 - Solid State Recorder
 - For matrix C&DH will consist of the flight computers and SSR's
- Attitude and Articulation Control Subsystem
 - Software run in SCP
 - Pointing normally from 4 reaction wheel subassemblies
 - Sun sensor
 - IMU
 - Mars Horizon Sensor Assembly
 - Celestial Sensor Assembly
- Telecommunications
 - One High Gain
 - 4 Low Gain – 2 transmit, 2 receive
 - Mars Orbiter Transponder
 - Command Detector Units
- Propulsion
 - Hydrazine tanks
 - Nitrogen tetroxide (NTO) tanks
 - Main engine – Only main engine uses bi-propellant
 - Attitude control thrusters – monopropellant
- Power
 - Solar arrays with aerobrake drag flaps
 - Nickel Hydrogen batteries

Case 6: Mars Climate Orbiter DSM Assumptions:

- Launch vehicle gives energy to the equipment and propulsion module structure – an energy transfer
- The propulsion module acts as a physical interface to the launch vehicle
- All active components have a physical and an energy interface to the power bus.
- All active components have a physical and an energy interface to heaters to maintain proper thermal conditioning and/or utilize some cooling from the louver system. Some heaters were thermostatically controlled, others were computer controlled.
- All powered components must release some of their energy through passive thermal control.
- All thrusters have a physical interface with and transfer energy to the propulsion structure.
- Thrusters and reaction wheels got indirect info from the attitude sensors but had physical and information interface to the central computer.
- The IMU was turned off except during major maneuvers so it was assumed it provided info indirectly only during correction firings.
- Only tanks and thrusters are located in the propulsion module.
- Thrusters have physical and energy interface to propulsion structure; reaction wheels transfer energy to equipment module structure.
- Deep Space Network gets energy and information from the spacecraft antennae.
- Software had indirect information exchange with sensors and effectors but direct information interface to the flight computer.
- Assume no solid state recorders used; data stored on central computer
- Assume the following component technology risk factors:
 - Propulsion system used new operation approach – late pressurization of propulsion; this would give TRF of at least 2 to propulsion components.
 - The central computer processor was developed for Mars Pathfinder but in this application was used as an all-in-one processor, which is a different application than Pathfinder, thus $TRF \geq 2$.
 - UHF link from orbiter to lander has $TRF \geq 2$
 - IMU being turned off – $TRF = 2$.
- Assume the science instruments are essential for their operational use (even though one instrument loss could still permit some degraded operations).

Case 7: Mars Polar Lander DSM Assumptions:

- There are 3 major spacecraft structures: cruise stage; entry vehicle, and lander
- Cruise stage primary components: attitude sensors, solar arrays, cruise antennae and telecommunications electronics.
- Cruise attitude control comes from thrusters and IMUs located on the lander
- Launch vehicle gives energy to all structure – an energy transfer, but only has a physical interface to the cruise structure
- All active components have a physical and an energy interface to the power bus.
- All active components have a physical and an energy interface to heaters to maintain proper thermal conditioning.
- All powered components must release some of their energy through passive thermal control. For the lander, this includes the loop heat pipe
- All thrusters have a physical interface with and transfer energy to the lander structure; there is an energy interface to the cruise structure.
- Thrusters get indirect info from the attitude sensors but had physical and information interface to the central computer.
- Thrusters used during cruise, entry and powered descent
- Tanks and thrusters are located in the lander structure.
- Parachute has an energy and physical interface to the aeroshell
- Deep Space Network gets energy and information from the spacecraft antennae.
- Software had indirect information exchange with sensors and effectors but direct information interface to the flight computer.
- Assume no solid state recorders used; data stored on central computer
- Assume the following component technology risk factors:
 - Powered descent is new for this heritage spacecraft (not used since Viking); this would give TRF of at least 2 to propulsion components.
 - The central computer processor was developed for Mars Pathfinder but in this application was used as an all-in-one processor, which is a different application than Pathfinder, thus TRF ≥ 2 .
 - UHF link from orbiter to lander has TRF ≥ 2
 - Parachute, aeroshell have pathfinder heritage, so TRF = 1
- Assume the science instruments are essential for their operational use (even though one instrument loss could still permit some degraded operations).